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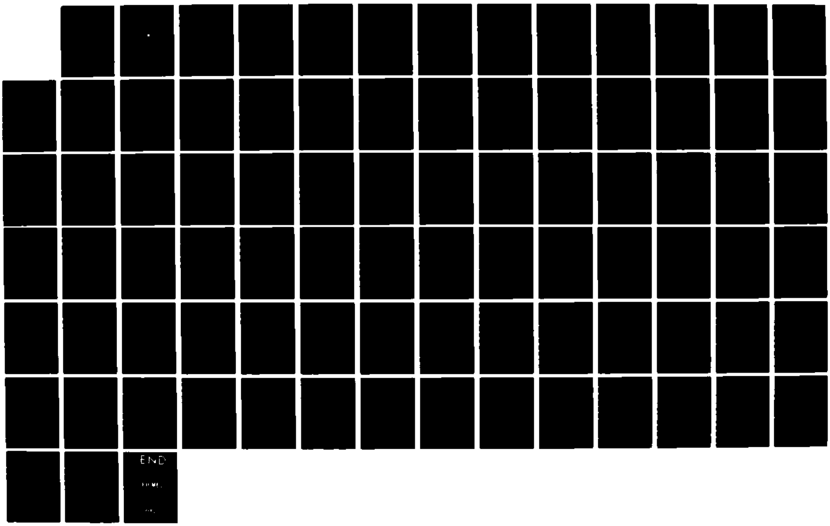

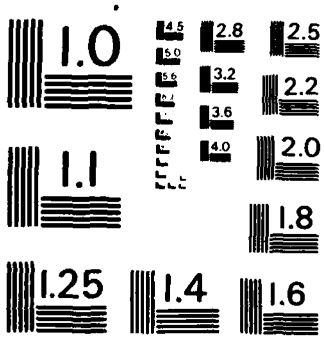

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AN ANALYSIS OF SOUND VELOCITY VARIATION IN AN ESTUARY FOR NOS STANDARDS

by

John D. Wilder

September 1985

Thesis Advisor: G. R. Schaefer

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Confidence intervals associated with sound velocity predictions provided by regression analyses showed a substantial improvement in accuracy when compared to using a single average velocity for each location. Nevertheless, there were still some cases where the NOS requirement could not be met.

An Analysis of Sound Velocity Variation in an Estuary for NOS Standards

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Investigation of oceanographic data acquired in the Columbia River estuary, which lies between the states of Washington and Oregon, revealed significant variation in sound velocity with respect to time and location. National Ocean Service (NOS) standards for echo-sounder acquired soundings require the knowledge of sound velocity to within plus or minus 4 meters per second. To meet this requirement in the Columbia River estuary, methods were devised to allow prediction of sound velocity based on location and the height of tide.

Confidence intervals associated with sound velocity predictions provided by regression analyses showed a substantial improvement in accuracy when compared to using a single average velocity for each location. Nevertheless, there were still some cases where the NOS requirement could not be met.

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I. INTRODUCTION

A. NOS HYDROGRAPHY

"Hydrography is that branch of physical oceanography dealing with the measurement and definition of the configuration of the bottoms and adjacent land areas of oceans, lakes, rivers, harbors, and other water forms on earth" [Ref. 1: p. 1-3]. The National Ocean Service (NOS) is the federal agency responsible for producing accurate nautical charts of nearshore areas of the United States and its territorial possesions. The principal objective of most hydrographic surveys conducted by NOS is to obtain basic data for the compilation of nautical charts with emphasis on the features that may affect safe navigation [Ref. 1: p. 1-3]. For this thesis data analysis is limited to the study of sound velocity variations and the correction of echo soundings for NOS hydrographic surveys. The type of data used for this investigation is often the basis for other physical studies such as the dynamics of oceanic mixing and salt transport. No attempt will be made to analyze or explain such processes.

1. *Sound Velocity and Sound Speed*

Manuals and papers about hydrographic surveying often use the term "sound velocity" to designate what a physicist would define as "sound speed." The term "sound velocity" will be used in this thesis as many of the references also use the term.

2. *Echo Sounding*

Echo sounders are the basic tool of the NOS hydrographer for determination of depth. Echo sounders measure the time required for a sound wave to travel from its point of origin to the bottom and return. They also convert this measured time to distance or depth [Ref. 1: p. AG-1]. The basic formula for echo sounder depth determination is:

$$Z = VT/2 \tag{1.1}$$

where Z is the depth, V is the calibrated velocity of sound for the echo sounder, and T is the time between transmission and reception of the sound signal. For depths to be accurate precise measurements of time and a knowledge of the mean, or harmonic, sound velocity (Chapter II) are mandatory.

B. THE VELOCITY OF SOUND IN SEA WATER

Wilson [Ref. 2: p. 641] developed empirical equations based on laboratory measurements of sound velocity under tightly controlled conditions. The basic equation is:

$$V = 1449.14 + V_T + V_P + V_S + V_{STP} \tag{1.2}$$

where V is the velocity of sound in meters per second, V_T is a correction for temperature, V_P is a correction for pressure, V_S is a correction for salinity, and V_{STP} is a simultaneous correction for the combined effects of temperature, salinity, and depth [Ref. 1: p. 4-75]. Wilson's equations (Chapter II), which are currently used by NOS, were chosen to analyze the data for this thesis.

C. NOS ACCURACY REQUIREMENTS

The sound velocity at which NOS echo sounders are calibrated is 800 fathoms per second. To obtain accurate depths for nautical charts the hydrographer must correct all soundings where the velocity of sound deviates from the calibrated value. There are several methods available for determining corrections for soundings, and they will be discussed in the following section. The NOS accuracy requirements [Ref. 1: p. 4-70] are:

> For use in correcting echo soundings, the velocity of sound must be known with sufficient accuracy to ensure that no sounding will be in error by as much as 0.25 percent of the depth from this cause alone. Therefore, the mean velocity must be known to

within plus or minus 4 meters per second. To satisfy these accuracy requirements, one must know the mean temperature of the water to an accuracy of plus or minus 1 degree Celsius and the salinity to within plus or minus 1 part per thousand. A sufficient number of salinity and temperature observations must be made so that the velocity can be determined within the specified accuracy over the entire area sounded.

D. PROCEDURES FOR CORRECTING SOUNDINGS

Echo soundings can be corrected by either a direct comparison or an oceanographic procedure. Direct comparisons involve comparing echo soundings to known depths; this does not require a knowledge of the sound velocity. Procedures which involve the calculation of sound velocity from measurements of water characteristics are classified as "oceanographic and limnologic determinations" [Ref. 1: p. 4-74]. For this thesis the direct measurement of sound velocity by a sound velocimeter is also classified as an oceanographic procedure.

1. *Direct Comparison Systems*

Two procedures used to determine depth corrections by the direct comparison method are the bar check and the vertical cast. In these the effects of sound velocity variation and instrument error are included in the results [Ref. 1: p. 4-71].

a. Bar Check

The bar check procedure involves lowering a bar over the side of a survey vessel and positioning the bar under the transducer at a known depth indicated by markings on the lines supporting the bar. Comparisons between the depth as indicated by the echo sounder and the known depth are made at 5- or 6-foot increments as the bar is lowered and raised though the water column. Due to the handling of the bar, this procedure is usually limited to smaller vessels and the quality of the results is a function of sea conditions. Observations during rough seas are subject to unacceptable magnitudes of error [Ref. 1: p. 4-71].

b. Vertical Cast

The vertical cast requires simultaneous sounding of the bottom using an echo sounder and a lead line. This procedure, which can be accomplished by practically all survey vessels, is not as accurate as the bar check, but vertical casts can be used to determine or verify instrument errors. Where sounding sheets junction, there are often discrepancies and soundings fail to agree. Vertical casts can sometimes help resolve such problems [Ref. 1: p. 4-72].

2. *Oceanographic Sound Velocity Determinations*

The more traditional oceanographic procedures involve sound velocity determination by measurement of the variables which enter Equation 1.2, namely temperature and salinity as functions of depth. The Nansen cast and electronic sensors such as the CTD (conductivity, temperature, and depth) or the STD (salinity, temperature, and depth) are examples of equipment used for these procedures. An alternative is the direct measurement of sound velocity using a sound velocimeter. The electronic sensors record data almost continuously with depth. [Ref. 1: p. 4-74].

To obtain velocity corrections with Nansen, STD, or CTD data, Umbach [Ref. 1: p. 4-75] recommends using the "summation of layers" method, which extends from the concept of mean or harmonic sound velocity.

Most of the electronic sensors which are currently in use yield precise measurements in excess of NOS accuracy requirements for sound velocity corrections if properly calibrated and maintained [Ref. 1: p. 4-74]. According to NOS standards all electronic sensors must be periodically checked for accuracy against Nansen cast or equivalent observations.

E. SOUND VELOCITY VARIATION

The effect of changes in temperature, salinity, and pressure on sound velocity depends upon the initial conditions of these variables.

Wilson's equations are used to illustrate in Table I the effect of changing variables by one unit.

TABLE I

Variation of Sound Velocity

PRES db	TEMP °C	SAL g/kg	V m/s	delta V m/s
1.00	15.00	30.00	1502.90	
1.00	14.00	30.00	1499.30	3.60
1.00	5.00	30.00	1464.27	
1.00	4.00	30.00	1460.03	4.25
1.00	10.00	35.00	1490.76	
1.00	10.00	34.00	1489.48	1.28
1.00	10.00	1.00	1449.01	
1.00	10.00	0.00	1447.84	1.17
60.00	10.00	30.00	1485.33	
59.00	10.00	30.00	1485.32	0.02
1.00	10.00	30.00	1484.38	
0.00	10.00	30.00	1484.36	0.02

Velocity (V) was computed using Wilson's equations.

Corrections for sound velocity variations in estuaries can present the hydrographer with a difficult task. According to Cameron and Pritchard [Ref. 3: p. 306], an estuary is a semi-enclosed coastal body of water having a free connection with the open sea and within which the sea water is measurably diluted with fresh water deriving from land drainage. Estuaries are extremely dynamic systems. Topography, river flow, and tidal action are important factors that influence the rate and extent of mixing salt and fresh water [Ref. 4: p. 4]. For the hydrographer, estuaries are areas where sound velocity varies not only

with location but also in time due to the tidal cycle and variations in river flow. Although no specific procedures are given, Umbach [Ref. 1: p. 4-75] notes the possible complexity of such areas:

> Under special circumstances such as . . . in areas of extensive estuarine discharge of fresh water . . . series of regional velocity curves are required. Regional curves must be carefully studied to determine how they can be best grouped by area or time or to permit drawing of average curves.

F. OBJECTIVES

One objective of this thesis was to investigate the magnitude of sound velocity variation associated with significant changes in water characteristics within an estuary.

A second objective was to investigate the feasibility of determining velocity corrections according to NOS standards in areas where extreme changes in water characteristics occur with respect to space and time.

A third objective was to write a FORTRAN program to enable further testing by the field hydrographer equipped with a personal computer. The use of commercial subroutines has been avoided.

II. METHODOLOGY AND PROCEDURE

A. AREA OF STUDY

The Columbia River estuary which discharges into the Pacific Ocean at latitude 46°15'N, longitude 124°00'W has variations in water characteristics which make it an excellent area for investigation. According to Dyer [Ref. 4: p. 96], the Columbia River estuary is characterized by an unusual combination of large river discharge and strong tidal currents. Recent investigations have revealed differences in salinity of up to 30 grams per kilogram at individual stations during a single tidal cycle [Ref. 5: p. 104]. Due to this large difference and the availability of data from a recently completed survey, this region was chosen for investigation.

B. DATA SOURCES

To analyze the problem completely, water characteristics (temperature and salinity as functions of depth) must be known at stations spaced throughout the region, and each station occupied during a complete lunar tidal cycle. Variations caused by seasonal changes in fresh-water runoff should be examined thoroughly.

1. *Columbia River Estuary Data Development Program*

The Columbia River Estuary Data Development Program (CREDDP) was a 5-year, federally funded study which included approximately 2 years of data acquisition for investigation of physical and biological characteristics. CREDDP was designed to meet the needs of two major groups. One group consisted of local, state, and federal government agencies involved in planning and permitting activities. The second group included research scientists and educational institutions [Ref. 6: p. v].

One accomplishment of CREDDP was the acquisition of current velocity, conductivity, temperature, and depth (VCTD) data for a better understanding of physical processes such as currents, sediment transport, and salinity intrusion. VCTD profiling was carried out for 13 consecutive days from 17 stations for periods of from 12 to 48 hours per station. Between October 16 and 27, 1980, approximately 1600 VCTD casts were made. Of these, 458 casts were made available to users [Ref. 6: p. L-8].

Data were supplied to NPS by the U.S. Army Corps of Engineers (COE) at Portland, Oregon, on two 9-track magnetic tapes [Ref. 6: pp. 1-5].

For an analysis of sound velocity variation, VCTD casts from 11 of the 17 stations were investigated. The stations, along with their positions and times are listed in Table II. The plot of the geographical positions of the stations is shown in Figure 2.1. These stations covered the area where the maximum sound velocity variation would be expected as deduced from salinity intrusion diagrams of the estuary [Ref. 5: p. 104].

2. *NOS Bar Check Data*

NOS bar check data were used for a sound velocity variation analysis. The descriptive report for survey H-8422 listed the day each bar check was taken and the correction for each 5-foot increment of depth. Also given was a general term for the stage of the tide such as ebb, flood, high water, or low water. Data for 46 bar checks were acquired between May 9 and July 16, 1958 [Ref. 7: p. 1].

3. *NOS Predicted Tide Data*

NOS predicted tide data were obtained for correlation and regression with the CREDDP and the H-8422 bar check data. Predicted tides were used because field hydrographers rarely have the time or the proper tools for a detailed analysis of real tide data.

TABLE II

Columbia River Estuary Data Development Program

STATION (STN) INFORMATION

STN	POSITION	ACQUISITION TIMES (PDT) START		END	
2N	46°15'45"N 124°03'31"W	10/18/80	0930	10/19/80	0230
2S	46°15'13"N 124°03'20"W	10/18/80	1230	10/19/80	0930
4NA	46°14'03"N 123°56'09"W	10/20/80	2115	10/21/80	1745
4NB	46°14'47"N 123°55'53"W	10/20/80	2105	10/21/80	1730
4SA	46°12'42"N 123°57'09"W	10/26/80	0007	10/27/80	0832
4SB	46°12'51"N 123°56'55"W	10/25/80	2350	10/27/80	0820
5NA	46°13'55"N 123°53'17"W	10/20/80	1733	10/22/80	0930
5NB	46°14'18"N 123°53'14"W	10/20/80	2035	10/22/80	0913
5NC	46°14'07"N 123°53'14"W	10/21/80	0935	10/22/80	1003
5SA	46°11'55"N 123°48'38"W	10/24/80	0830	10/25/80	2331
5SB	46°12'05"N 123°48'54"W	10/24/80	1126	10/25/80	1130

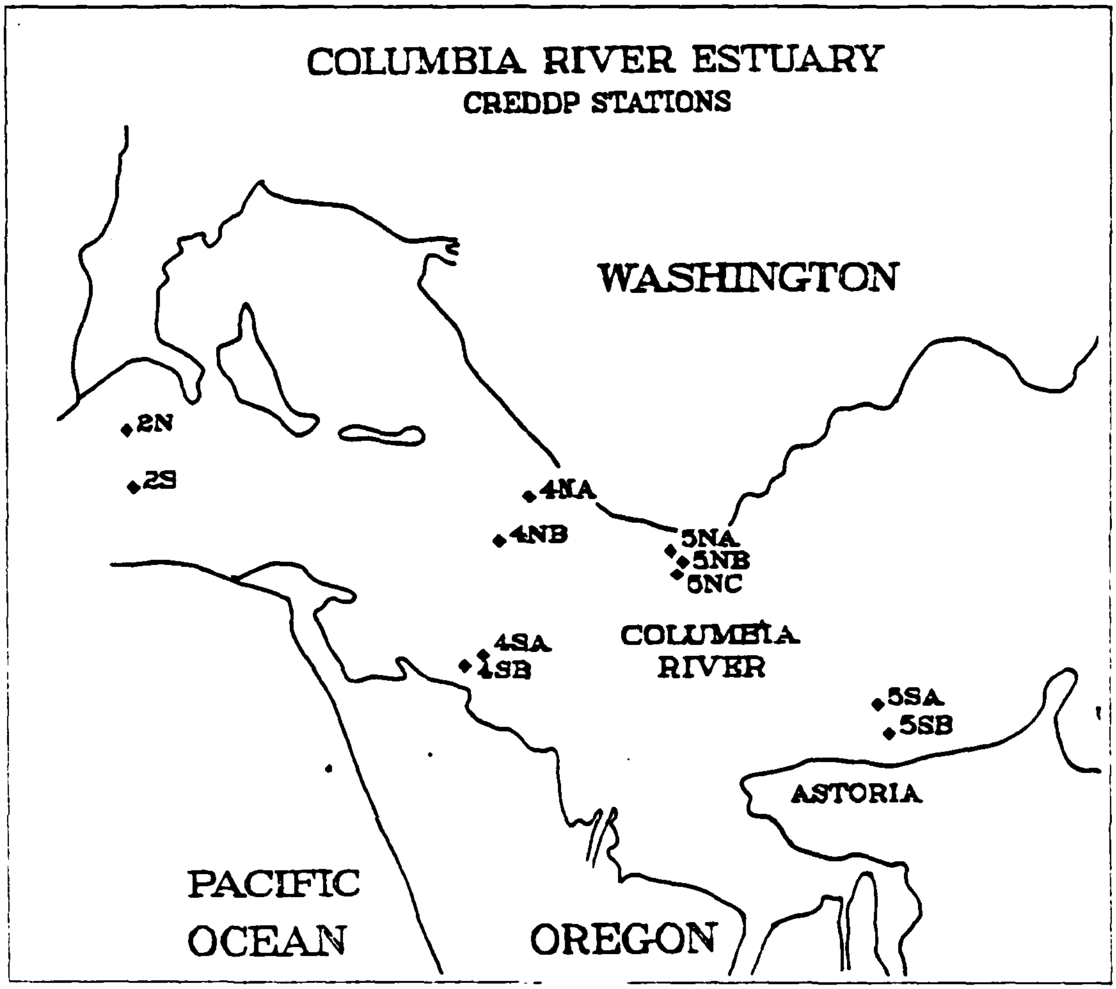

Figure 2.1 CREDDP Stations.

C. CREDDP DATA ANALYSIS

1. *COE VCTD Data Tapes*

COE VCTD data tapes contained pertinent information such as header data, time, temperature, depth, conductivity, and salinity. Mercier [Ref. 6: p. L-8] shows a breakdown of the data components for one record of data. The tapes contained more data records than were necessary for this investigation. The VCTD sampling device recorded data every 0.04 seconds, thereby making the average number of

records for a single cast approximately 1500. Having 270 casts to analyze, a method was devised to reduce the data to a more efficient size. A computer program was formulated to input the data for each cast and then output the first record and the records which corresponded to the nearest whole meter of depth. For example, a 10-meter cast would theoretically have 11 records of data; the first record would represent the surface layer, and the remaining 10 records would be for 1-meter increments. In accordance with the NOS policy of using bar check data measured at 5- or 6-foot increments, data were eliminated except at 1-meter increments. A sample of a profile after editing is shown in Table III. Standard depths which represent depths of 1, 3, 5, 7, 9, 11, and 13 meters, were adopted to further simplify data processing and description.

Several drawbacks were encountered using the CREDDP data. Because of the shallow depths of CREDDP stations, many of the casts were inadequate for correcting soundings in the deeper areas of the estuary. Some casts did not include surface layer data (0 to 2 meters).

2. *Sound Velocity Computations*

a. Wilson's Equations

Sound velocity was computed for each record by Wilson's equations which use temperature, pressure, and salinity for the computation. In the following equations V is sound velocity in meters per second; T is temperature in degrees Celsius, where $-4 < T < 30$ °C; P is pressure in kilograms per square centimeter, where $1 < P < 1000$ kg/cm^2; and S is salinity in grams per kilogram, where $0 < S < 37$ g/kg.

$$V = 1449.14 + V_T + V_P + V_S + V_{STP} \quad (2.1)$$

$$V_T = 4.5721T - 4.4532\times10^{-2}T^2 - 2.6045\times10^{-3}T^3 + 7.9851\times10^{-6}T^4 \quad (2.2)$$

$$V_P = 1.60272\times10^{-1}P + 1.0268\times10^{-5}P^2 + 3.5216\times10^{-9}P^3 - 3.3603\times10^{-12}P^4 \quad (2.3)$$

$$V_S = 1.39799(S-35) + 1.69202\times10^{-3}(S-35)^2 \quad (2.4)$$

$$V_{STP} = (S-35)(-1.1244\times10^{-2}T + 7.7711\times10^{-7}T^2 + 7.7016\times10^{-5}P - 1.2943\times10^{-7}P^2 + 3.1580\times10^{-8}PT + 1.5790\times10^{-9}PT^2) + P(-1.8607\times10^{-4}T + 7.4812\times10^{-6}T^2 + 4.5283\times10^{-8}T^3) + P^2(-2.5294\times10^{-7}T + 1.8563\times10^{-9}T^2) + P^3(-1.9646\times10^{-10}T) \quad (2.5)$$

The standard deviation for the velocity is 0.30 meters per second [Ref. 8: p. 1357].

TABLE III

4SA--Cast 6--*Sound Velocity Variables*

COLUMBIA RIVER

STATION = 4SA CAST = 031B08
LATITUDE 46°12'42"N LONGITUDE 123°57'09"W
DATE OF CAST 1980 OCT 26 TIME OF CAST 5:16: 0

TIME s	PRES db	CTD DEPTH m	TEMP °C	COND ratio	SAL g/kg
0.04	-0.04	0.10	12.26	0.4531	15.71
5.48	0.85	1.00	12.04	0.5252	18.57
12.04	1.86	2.01	11.79	0.7073	25.91
18.48	2.85	3.00	11.78	0.7571	27.95
24.60	3.86	4.01	11.78	0.7932	29.42
31.52	4.86	5.00	11.79	0.8184	30.46
37.68	5.90	6.04	11.79	0.8164	30.37
43.80	6.86	7.00	11.80	0.8232	30.64
50.48	7.88	8.01	11.81	0.8291	30.88
56.80	8.89	9.01	11.81	0.8302	30.92
63.32	9.88	10.00	11.81	0.8330	31.04
69.92	10.91	11.03	11.82	0.8338	31.07
76.12	11.90	12.01	11.82	0.8356	31.14
82.84	12.90	13.01	11.82	0.8346	31.10

b. Mean Sound Velocity

Because echo sounders are time measuring devices, distance or depth is one-half the round trip travel time of a sound pulse multiplied by a suitable mean velocity. The mean sound velocity (MSV) is given by

$$MSV = Z/T \tag{2.6}$$

where Z is the distance traveled in time T. To correct for sound velocity variations, the water column is divided into a series of layers, each with thickness ΔZ_i and an associated velocity V_i. Therefore, the time interval for the sound wave to pass through the i^{th} layer is:

$$\Delta T_i = \Delta Z_i / V_i \tag{2.7}$$

Summing all layers results in:

$$T = \sum_{i=1}^{n} \Delta T_i = \sum_{i=1}^{n} \Delta Z_i / V_i \tag{2.8}$$

or:

$$T = \int_0^Z dZ/V \tag{2.9}$$

Substituting into Equation 2.6 results in:

$$MSV = Z/(\int_0^Z dZ/V) \tag{2.10}$$

Equation 2.10 was evaluated using the trapezoidal method [Ref. 9: p. 86]. NOS uses mean sound velocities in the "summation of layers" method described by Umbach [Ref. 1: p. 4-74] and Wallace [Ref. 10: p. RK530.1].

Two sound velocity listings computed using the data in Table III are shown in Table IV. The sound velocity column was

computed using Equation 2.1, and the mean velocity column was computed using Equation 2.10.

TABLE IV

4SA--CAST 6--Sound Velocity Data

DATE: 26 OCTOBER 1980
TIME: 0520 (PDT)

DEPTH m	SOUND VELOCITY m/s	MEAN VELOCITY m/s
0.10	1475.5	1475.5
1.00	1478.1	1476.8
2.01	1486.1	1479.6
3.00	1488.6	1482.2
4.01	1490.5	1484.1
5.00	1491.8	1485.5
6.04	1491.7	1486.6
7.00	1492.1	1487.3
8.01	1492.5	1488.0
9.01	1492.5	1488.4
10.00	1492.7	1488.9
11.03	1492.8	1489.3
12.01	1492.9	1489.5
13.01	1492.9	1489.8
14.01	1492.9	1490.0

To simplify the analysis of the variation of mean sound velocity as a function of time, a computer program was written to arrange the data in individual arrays for each depth at each station.

3. *Mean Sound Velocity and Tide Height*

Inspection of the mean sound velocity arrays suggested that velocities were maximum at high tide and minimum at low tide. To test this, a correlation and regression analysis between the CREDDP derived mean sound velocities and predicted tide heights was performed.

a. Predicted Tide Heights

To perform the correlation and regression analysis, a method had to be developed to calculate the height of the tide at any desired time. One method would be to obtain the harmonic constants for prediction of the Columbia River estuary tides from the NOS Tides and Water Levels Branch. These constants would then be used in the appropriate equations [Ref. 11: p. 123]. From a computer programming standpoint this method would be the simplest. A second method would be to formulate a computer program based on the graphical method (Figure 2.2) described in the NOS Hydrographic Manual [Ref. 1: p. 4-68]. This method was chosen because normally the field hydrographer is not supplied with the harmonic constants for project areas. However, the tide tables are an essential tool of the hydrographer.

The present NOS HYDROPLOT computer program for tide prediction lacks documentation and is not designed to solve this particular problem [Ref. 10: p. 500.1]. Therefore, a program was written.

Points A and E (Figure 2.2) represent the predicted low and high tide, respectively. The straight line between these points was divided into four equal parts by points B, C, and D. Point B' was plotted directly below B at one-tenth the total range, and point D' was plotted directly above D using the same distance [Ref. 1: p. 4-68], forming three regions for the solution of predicted heights between points A and E. For the region between points A and B', the curve was assumed to be parabolic, and in order to calculate the tide height for a designated time in this region, the equation

$$H_i = aT_i^2 + bT_i + c \tag{2.11}$$

was used, where H is the tide height and T is the designated time. To calculate the coefficients a, b, and c; the equations

$$H_A = aT_A^2 + bT_A + c \tag{2.12}$$

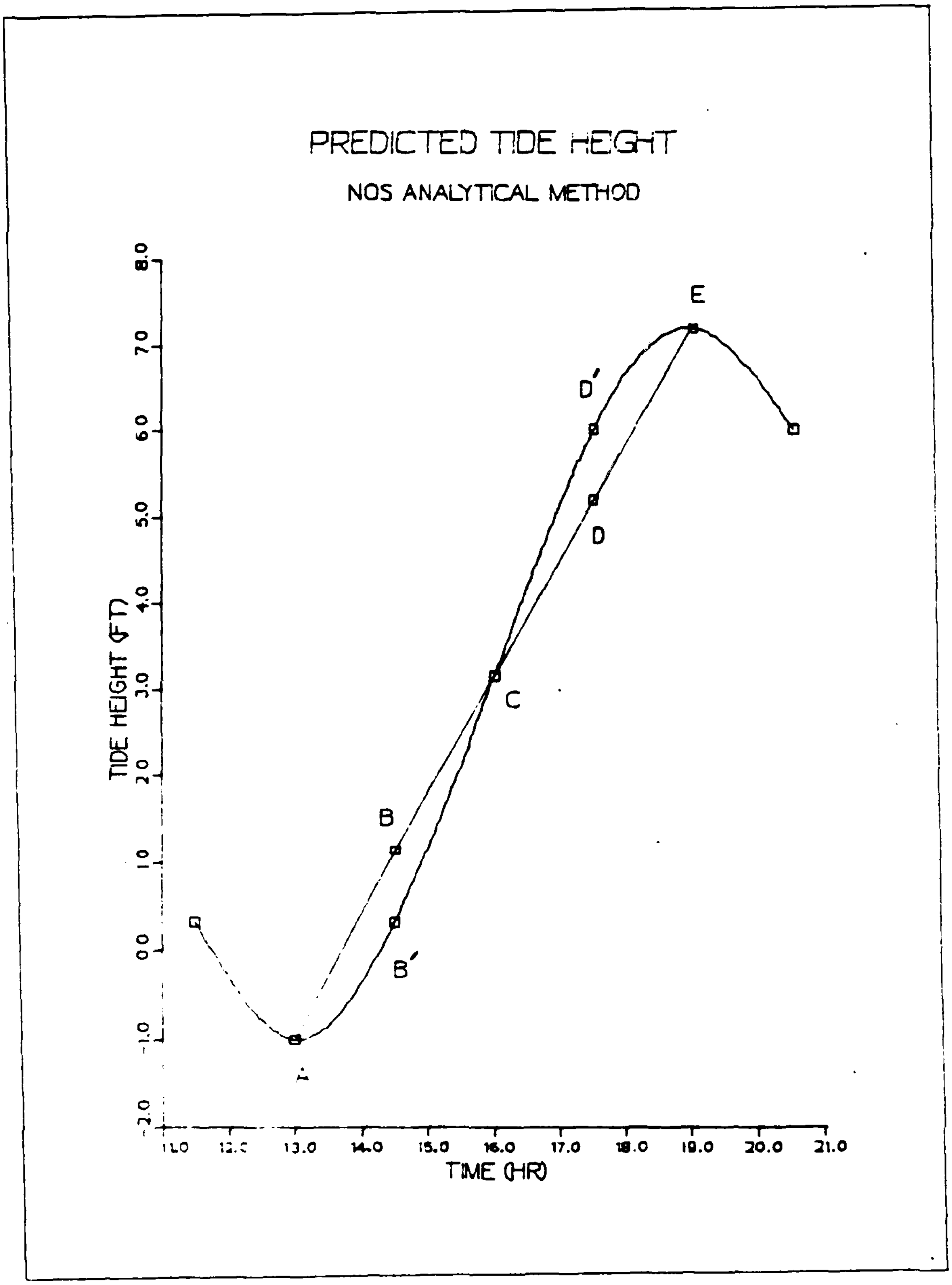

Figure 2.2 Predicted Tide Graph.

$$H_{B'} = aT_{B'}^2 + bT_{B'} + c \tag{2.13}$$

$$0 = 2aT_A + b \tag{2.14}$$

were used. For times that lie between points D' and E, the same method was used. Between points B' and D' the change in height was considered to be linear with respect to time and can be computed by the equation

$$H_i = H_{B'} + m(T_i - T_{B'}) \tag{2.15}$$

where m is the slope defined by

$$m = (H_{D'} - H_{B'})/(T_{D'} - T_{B'}) \tag{2.16}$$

Using the program based on the above equations, tide heights were calculated for the times of all VCTD casts used in the analysis. "Data Array" means a set of sound velocity and predicted tide height data that shows the variation of both variables with time for a particular station and depth (Table V).

b. Data Plots

Computer generated plots of predicted tide height and observed mean sound velocity (Figure 2.3) were made for all stations using mean velocities based on standard depths.

c. Correlation Analysis

A correlation analysis routine for mean sound velocity and tide height was run for all data arrays. In addition to computing the correlation coefficient, the routine also computed the averages and the standard deviations of the mean sound velocity and the predicted tide height for each data array. Averages were computed by the equation

$$\bar{x} = \sum_{i=1}^{n} x_i/n \tag{2.17}$$

TABLE V

4SB--Data Array--Depth = 7 m

TIME hr	TIDE HEIGHT ft	MEAN VELOCITY m/s
0.12	1.2	1469.6
1.50	4.1	1476.6
2.63	6.5	1486.5
3.60	7.6	1490.8
4.62	7.6	1490.8
5.27	7.1	1487.3
6.32	5.6	1483.1
9.23	1.7	1472.1
11.55	3.0	1471.0
12.58	4.9	1472.2
13.17	6.0	1476.9
17.53	7.7	1489.6
21.52	-0.8	1471.4
22.43	-1.5	1468.6
23.35	-1.3	1467.7
24.28	-0.2	1467.1
25.33	1.9	1470.0
26.42	4.1	1473.6
27.57	6.2	1480.0
28.48	7.2	1485.9
29.48	7.2	1491.9
30.50	6.4	1488.6
31.53	5.1	1485.4
32.53	3.8	1477.3

where x_i is the i^{th} observation and n is the number of observations [Ref. 12: p. 124]. Standard deviations [Ref. 12: p. 128] were computed using the formula

$$s = \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2/(n-1)} \qquad (2.18)$$

Computation of the simple correlation coefficient [Ref. 12: p. 258] of the mean sound velocity and predicted tide height arrays was done with equation

$$r = \frac{[n \sum_{i=1}^{n} x_i Y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} Y_i)]}{\sqrt{[n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2][n \sum_{i=1}^{n} Y_i^2 - (\sum_{i=1}^{n} Y_i^2)]}} \qquad (2.19)$$

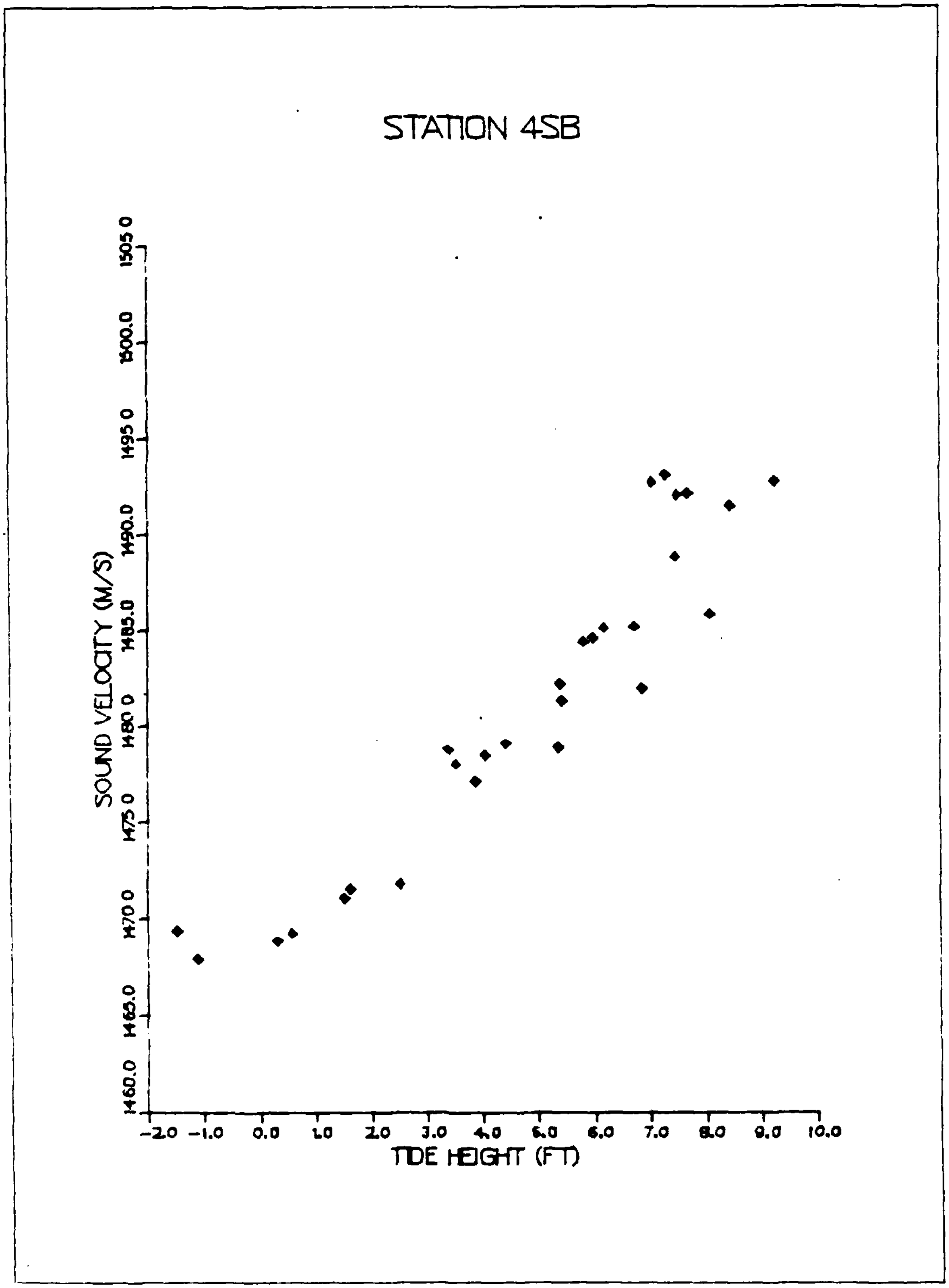

Figure 2.3 4SB--Data Array Plot--Depth = 7 m.

A sample of the results of a correlation analysis is listed in Table VI.

TABLE VI

4SB--Statistical Data--Depth = 7 m

AVERAGE TIDE HEIGHT	4.4 ft
STANDARD DEVIATION OF TIDE HEIGHT	3.0 ft
AVERAGE MEAN VELOCITY	1480.8 m/s
STANDARD DEVIATION OF MEAN VELOCITY	8.0 m/s
CORRELATION COEFFICIENT	0.93

d. Regression Analysis

To determine the feasibility of predicting mean sound velocity, a first-order (or linear) regression analysis was performed on all data arrays. The data were fitted to the equation

$$y = a + bx \qquad (2.20)$$

where y is the estimated mean velocity, a is the coefficient, b is the the intercept, and x is the tide height. The coefficient and intercept estimates were determined to minimize the sum of the residuals

$$\sum_{i=1}^{n} e_i = \sum_{i=1}^{n} (Y_i - y_i) \qquad (2.21)$$

where Y_i is the observed mean sound velocity and y_i is the estimated velocity [Ref. 13: p. 533]. Determination of the coefficients and the intercepts was accomplished by the normal equations

$$an + b\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} Y_i \quad (2.22)$$

$$a\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} x_iY_i \quad (2.23)$$

where n is the number of observations for a particular station and depth [Ref. 13: p. 533]. The sum of the squares of the residuals is

$$SS = \sum (Y_i - y_i)^2 \quad (2.24)$$

The standard error of estimate is

$$see = \sqrt{(SS / v)} \quad (2.25)$$

where v is the degrees of freedom given by

$$v = p - n \quad (2.26)$$

where n is the number of sample observations and p is the number of estimated variables [Ref. 14: p. 131]. For a first-order analysis, there are two estimated variables. Results of a first-order analysis are listed in Table VII.

Confidence intervals associated with predicted mean velocities obtained by equations derived from the linear regression analysis were calculated to determine the accuracy of predictions. Confidence interval computation requires the standard error of estimate, the value of the student-t (t) distribution which is based on the desired percent of confidence, and the degrees of freedom for the sample. For this thesis, 90-percent confidence intervals were computed using the equation

$$CI = \pm\, t(v,0.95)[1 + (1/n) + [(x_i-\bar{x})^2 / \sum_{i=1}^{n} (x_i-\bar{x})^2]]see \quad (2.27)$$

TABLE VII

4SB--Linear Regression--Depth = 7 m

COEFFICIENT = 2.8
Y INTERCEPT = 1468.0

CAST	MEAN VELOCITY RESIDUAL
1	-0.3
2	0.2
3	0.2
4	3.2
5	2.8
6	0.1
7	-5.1
8	-0.8
9	-1.7
10	-1.2
11	-1.0
12	-1.4
13	0.1
14	-0.9
15	-4.5
16	-4.0
17	1.4
18	5.0
19	7.2
20	5.5
21	2.9
22	0.0
23	-3.2
24	-1.2
25	0.0
26	5.1
27	4.8
28	0.0
29	-1.7
30	-0.8
SS	244.8
see	3.0

A RESIDUAL IS THE DIFFERENCE BETWEEN THE OBSERVED MEAN VELOCITY AND THE PREDICTED MEAN VELOCITY.

where CI is the confidence interval for a single estimated velocity (y_i), x_i is the tide height, $\overline{x}$ is the mean tide height, and n is the number of sample observations [Ref. 15: p. 30].

Several plots of the data arrays indicated a curvilinear relationship between mean sound velocity and predicted tide height. Therefore, second- and third-order polynomial regression analyses were performed on all data arrays to provide a better fit of the data, thereby increasing the accuracy of the mean sound velocity prediction. The normal equation method used in the first-order analysis was extended for calculation of a second-order polynomial. To check the results of the programs for the normal equation method, a subroutine using the orthogonal polynomial method was obtained from the NPS Computer System Library [Ref. 16: p. 8]. A third-order regresssion analysis was also performed by the orthogonal polynomial subroutine to investigate the possibility of increasing the accuracy of prediction and fit. Based on results of the investigation and check (Chapter III), the first-order and second-order normal equation methods were designated as the primary methods of analysis. The normal equation method appeared to be the simplest to program. The second-order analysis uses the equation

$$y = a_0 + a_1 x + a_2 x^2 \tag{2.28}$$

where y represents the estimated mean sound velocity and x is the predicted tide height [Ref. 13: p. 535]. Coefficients (a_0, a_1, and a_2) were determined to minimize the sum of residuals by the following normal equations

$$a_0 n + a_1 \sum_{i=1}^{n} x_i + a_2 \sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} Y_i \tag{2.29}$$

$$a_0 \sum_{i=1}^{n} x_i + a_1 \sum_{i=1}^{n} x_i^2 + a_2 \sum_{i=1}^{n} x_i^3 = \Sigma x_i Y_i \tag{2.30}$$

$$a_0 \sum_{i=1}^{n} x_i^2 + a_1 \sum_{i=1}^{n} x_i^3 + a_2 \sum_{i=1}^{n} x_i^4 = \sum_{i=1}^{n} x_i^2 Y_i \tag{2.31}$$

where n is the number of casts for a particular station and depth [Ref. 13: p. 536]. Results of a second-order analysis are listed in Table VIII.

TABLE VIII

4SB--Polynomial Regression--Depth = 7 m

COEFFICIENTS

a_0 = 1470.0
a_1 = 1.6
a_2 = 0.1

CAST	MEAN VELOCITY RESIDUAL
1	-1.7
2	0.8
3	1.0
4	3.2
5	2.7
6	0.2
7	-4.7
8	0.6
9	-1.0
10	-1.7
11	-1.4
12	-0.9
13	-0.7
14	-2.4
15	-5.0
16	-3.2
17	2.0
18	4.2
19	5.3
20	1.4
21	-0.6
22	-1.7
23	-3.0
24	-0.4
25	0.8
26	5.4
27	5.0
28	0.7
29	-0.9
30	0.0
SS	209.8
see	2.8

A RESIDUAL IS THE DIFFERENCE BETWEEN THE OBSERVED MEAN VELOCITY AND THE PREDICTED MEAN VELOCITY.

Confidence intervals for predicted velocities were computed using Equation 2.27. The degrees of freedom for a second-order analysis was less than a first-order analysis because of the addition of one estimated variable.

D. NOS BAR CHECK DATA

The NOS bar check data consisted of 46 bar checks which were acquired to determine the corrections for soundings of survey H-8422. The format of the data was a listing of corrections for 5-foot increments of depth. The initial analysis included determination of the maximum, minimum, and mean correction for each depth (Table IX).

TABLE IX

Bar Check Correction Data For Survey H-8422

OBS	MEAN ft	UPPER LIMIT ft	LOWER LIMIT ft	RANGE ft	DEPTH ft
88	-1.0	-0.6	-1.4	0.8	5
90	-0.8	-0.2	-1.4	1.2	10
90	-0.7	-0.1	-1.4	1.3	15
90	-0.7	0.0	-1.3	1.3	20
90	-0.7	0.1	-1.4	1.5	25
87	-0.7	0.0	-1.6	1.6	30
82	-0.6	0.0	-1.3	1.3	35
73	-0.5	0.0	-1.2	1.2	40
30	-0.3	0.6	-1.1	1.7	45
12	-0.4	0.0	-1.0	1.0	50

For each depth of a bar check there were two corrections listed; the first correction was recorded as the bar was being lowered, and the second during raising. These two corrections were averaged to obtain a single value which was used for a correlation analysis with predicted tide height.

A plot of the bar check and tide height data (Figure 2.4) was made and visually examined. The plot indicates a poor correlation between bar check corrections and predicted tide heights. For verification, a correlation analysis (Table X) was performed using methods previously discussed.

TABLE X

Bar Check Statistical Data for Survey H-8422

MEAN TIDE HEIGHT	3.3 ft
STANDARD DEVIATION OF TIDE HEIGHT	2.9 ft
MEAN CORRECTION	-0.7 ft
STANDARD DEVIATION OF CORRECTION	0.3 ft
CORRELATION COEFFICIENT	0.12
DEPTH OF OBSERVATIONS	25.0 ft

Because of the poor correlation, actual tidal data were obtained to investigate the possiblilty that the results were related to the predicted tides. No improvement in the results was accomplished by using actual tide data. No further manipulation of the NOS bar check data was carried out because of the number of unknowns associated with the acquisition procedures and because the amount of speculation necessary could not lead to meaningful analysis.

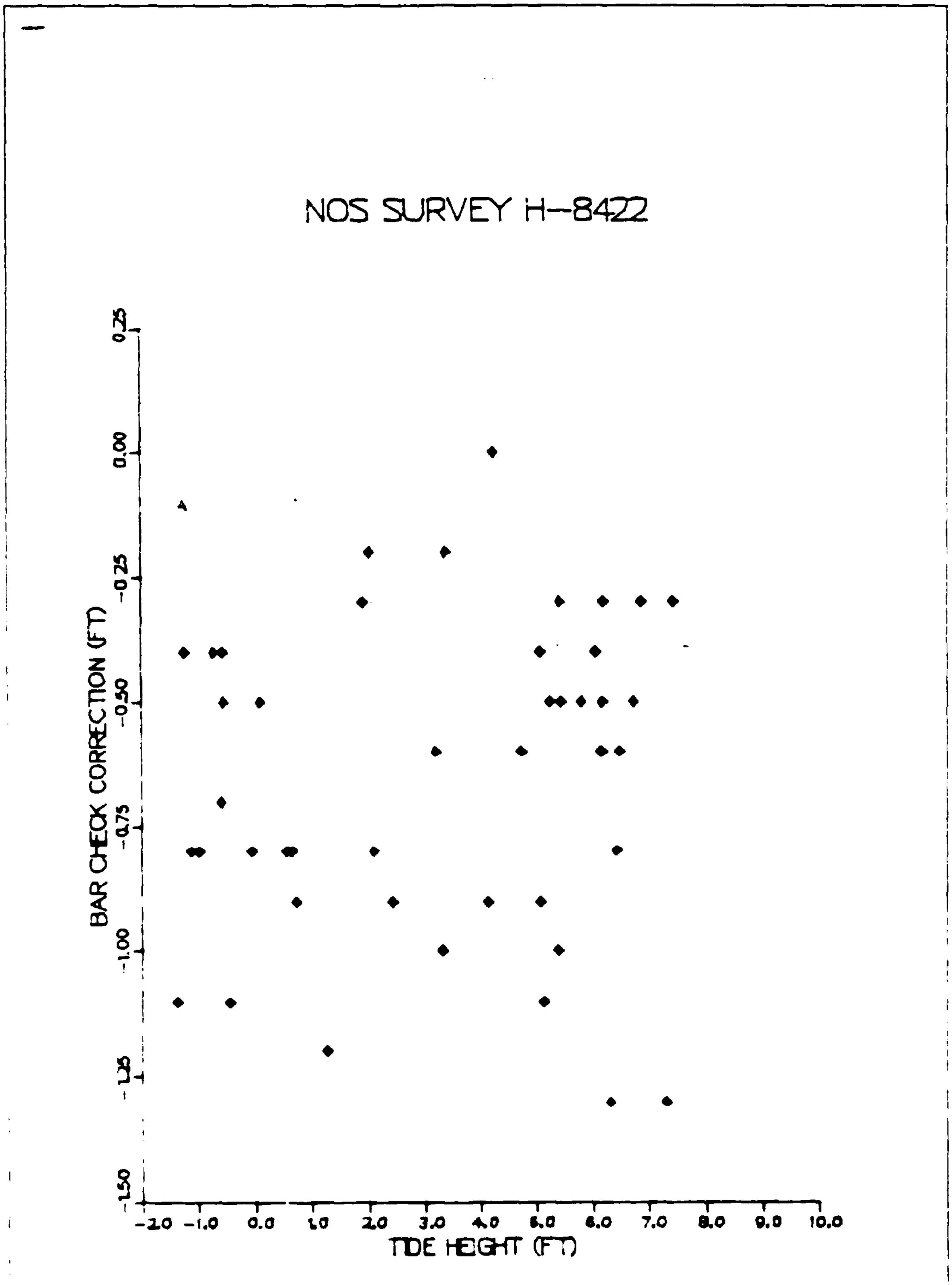

Figure 2.4 Bar Check Data Array--Depth = 25 ft.

III. DISCUSSION OF RESULTS

A. CREDDP DATA

Data acquisition procedures of CREDDP made an investigation of mean sound velocity variation possible, but there are factors which make the study incomplete. Because of this, a complete model for mean sound velocity prediction and correction based on methods presented in this thesis was not fully developed. However, the primary components of such a model were devised and will be explained in this chapter. The factors which make the investigation incomplete and recommendations concerning verification of ideas and methods presented in this thesis will be addressed in Chapter IV.

Investigation of the CREDDP data revealed that sound velocity in the Columbia River estuary varies with position, depth, and time. To analyze the problem the study area was divided into two primary sections, the north channel and the south channel (Table XI). The 'river mile' distance represents the shortest deep-water path from buoy "7" at the river entrance to the station. The south channel, which is maintained for commercial marine traffic, has a river mile scale which can be found on NOS chart 18521, whereas north channel stations were scaled using chart 18521.

Two categories of mean sound velocity variation are considered. The term "horizontal variation" designates differences in mean sound velocity between stations; i.e., how the velocity changes with location. The horizontal variation analysis is needed to develop zones or regions where velocity correctors may be grouped. The term "temporal variation" designates the change in mean sound velocity with time at each station. With temporal variation, mean sound velocity correctors for each zone change with time.

TABLE XI
Channel Data

north channel		south channel	
Station	River Mile	Station	River Mile
2N	2.0	2S	2.0
4NB	7.5	4SB	8.0
5NB	9.5	5SA	15.5

1. *Horizontal Variation*

For the analysis of horizontal variation the two requirements made were: (1) that for each depth there be but one horizontal variation analysis and; (2) the average of all mean velocities obtained at the depth being analyzed be designated as the average velocity. Use of the average velocity allows each station to have a single velocity for each depth. The average velocity presents a problem if more observations were made on one end of the tidal spectrum than the other. For example, if more casts were acquired during periods of high water than periods of low water, the average velocity would be higher than if the majority of casts were acquired during low water periods. One of the CREDDP objectives was to acquire casts on an hourly basis. This objective was met in most cases, but there were some instances where the time interval between successive casts was greater than 1 hour. For example, station 4SB was chosen over station 4SA for designation of the south channel because there were no casts acquired at station 4SA during the higher high tide. Another potential problem would be introduced if there were significant variations in the river flow. According to Jay **[Ref. 5: p. 114]**, river flow remained low for the acquisition period. An example of horizontal variation of the average velocity is shown in Figure 3.1. These plots indicate the rate of horizontal variation of the average velocity is approximately the same

for the north and south channels. Data for the 11- and 13-meter depths were limited and did not cover the range of tide well in many cases.

Regional zoning of mean sound velocity correctors based solely on horizontal variation can be accomplished with little difficulty. Using the depth with maximum horizontal variation, zones can be drawn based on the NOS criteria of plus or minus 4 meters per second. A major problem still exists in that the temporal variation of mean sound velocity has not been accounted for when only the horizontal variation of the average velocity is considered.

2. *Temporal Variation*

An analysis of temporal variation of the mean sound velocity demonstrated that proper correction of soundings in the Columbia River is a multi-dimensional problem. Sound velocity variables change significantly with time at the same location, and the magnitude of variation can depend on a number of cyclic and noncyclic phenomena. Sound velocity variables change with the tide, and the magnitude of the variation is affected by monthly tidal events such as spring and neap tides. The temporal and horizontal variations of velocity for the stations of the north and south channels are shown in Figure 3.1.

Data for stations 2N and 2S were acquired during a neap tide period when the predicted tide range was minimum, whereas data acquisition for stations 4SA, 4SB, 5SA, and 5SB was accomplished during a spring tide period. Data for stations 4NA, 4NB, 5NA, 5NB, and 5NC were acquired during a period of average tide range. As illustrated by Figure 3.1, stations 4NB and 4SB have about the same average velocity at the standard depths, but with respect to temporal variation, the range of velocity for station 4SB was significantly larger than that found at station 4NB. According to Jay [Ref. 5: pp 114,117], the neap tide period was a one of minimum vertical mixing and maximum stratification, whereas during the spring tide period, maximum mixing, minimum stratification, and maximum salinity intrusion occurred. Examination of the casts for stations 4NB and 4SB (Table XII)

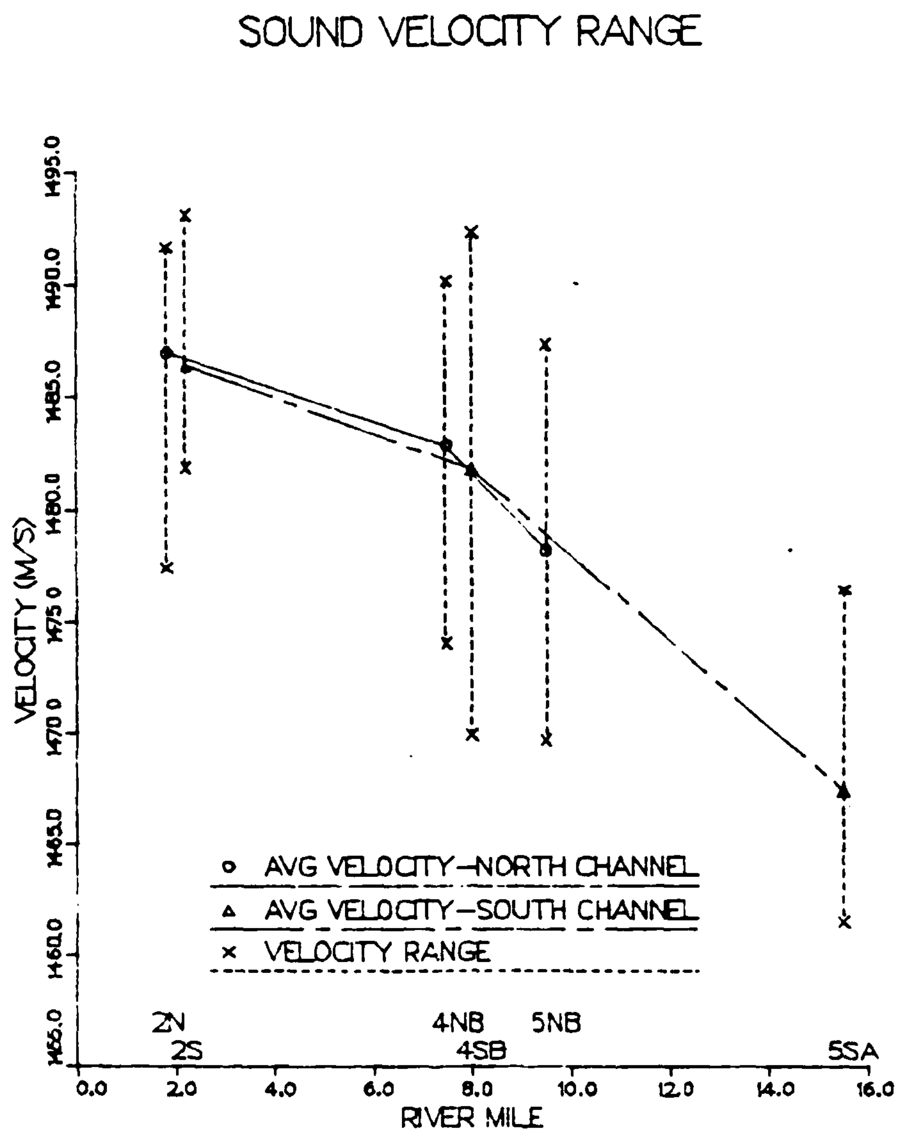

Figure 3.1 Temporal and Horizontal Variations of Velocity--Depth = 9 m.

confirmed the previous statement. The cast for station 4NB acquired at predicted low tide showed a significant difference in temperature when compared to the low tide cast of station 4SB. The warmer temperatures of the low tide cast caused the the minimum velocity to be higher at station 4NB than at station 4SB. Comparison of the high tide casts indicated the surface layer salinity was 6.82 parts per thousand less at station 4NB than at station 4SB. The relatively large salinity difference for the high tide casts caused the maximum mean velocity to be lower at station 4NB when compared to the maximum mean velocity at station 4SB. Therefore, the increased energy associated with a larger tide range can increase the mean sound velocity range for certain areas in two ways. First, increased mixing associated with the larger tide range can moderate temperature for low tide cast, thereby causing minimum mean velocities to be lower. Second, increased salinity intrusion associated with a larger tide range can cause maximum mean velocities to be higher when compared to maximum mean velocities observed during an average or neap tide range.

a. Correlation of Tide Height and Sound Velocity

The effort to correct mean sound velocity for temporal variation began with a correlation analysis of predicted tide height and mean sound velocity. The results (Table XIII) indicate a strong relationship between tide height and mean sound velocity for most of the CREDDP data. Correlation in the 1-meter layer was usually not as strong as the deeper layers for most of the stations. Dashed line entries in Table XIII indicate insufficient data for a correlation analysis.

b. Regression Analysis

First- (linear), second-, and third-order polynomial regression analyses were performed for each standard depth of the CREDDP sampling stations. The objective of these analyses was to provide a numerical method of predicting mean sound velocity using the predicted tide height. These methods would be considered completely

TABLE XII

The Effect of Tide Range on Mean Sound Velocity Range

STATION 4NB

TIDE HEIGHT = 0.02 ft (LOW TIDE)

DEPTH m	TEMP °C	SAL g/kg	VEL m/s
1.0	14.22	6.32	1472.2
3.0	14.14	7.48	1472.5
5.0	14.05	8.52	1473.1
7.0	13.93	9.73	1473.5

TIDE HEIGHT = 8.3 ft (HIGH TIDE)

DEPTH m	TEMP °C	SAL g/kg	VEL m/s
1.0	12.18	23.49	1484.6
3.0	11.78	29.26	1487.4
5.0	11.97	29.89	1489.2
7.0	11.66	30.19	1489.8

STATION 4SB

TIDE HEIGHT = -1.5 ft (LOW TIDE)

DEPTH m	TEMP °C	SAL g/kg	VEL m/s
1.0	12.71	8.41	1468.6
3.0	12.69	8.92	1468.9
5.0	12.66	9.55	1469.2
7.0	12.64	9.70	1469.4

TIDE HEIGHT = 9.2 ft (HIGH TIDE)

DEPTH m	TEMP °C	SAL g/kg	VEL m/s
1.3	11.88	30.31	1491.9
3.0	11.87	30.69	1492.1
5.0	11.84	31.35	1492.5
7.0	11.84	31.48	1492.7

successful if the confidence interval for predictions based on all possible tide heights was less than, or equal to, plus or minus 4 meters per second. The employment of three different orders of polynomial

TABLE XIII

Correlation Coefficients

STN	1m	3m	5m	DEPTH 7m	9m	11m	13m
2N	0.61	0.81	0.85	0.87	0.87	0.87	0.78
2S	0.86	0.68	0.79	0.83	0.88	0.89	0.85
4NA	0.83	0.91	0.94	0.97	0.98	0.99	0.99
4NB	0.81	0.90	0.94	0.96	0.96	0.99	----
4SA	0.71	0.82	0.86	0.89	0.92	0.90	0.93
4SB	0.75	0.83	0.89	0.93	0.96	0.99	----
5NA	0.86	0.89	0.92	0.91	0.90	----	----
5NB	0.80	0.86	0.91	0.94	0.95	0.97	0.96
5NC	0.90	0.91	0.91	0.94	0.96	0.97	0.97
5SA	0.89	0.88	0.88	0.87	0.85	0.86	----
5SB	0.88	0.88	0.88	0.87	0.86	----	----

regression analysis was for comparison of fit, as well as comparison of the predicted velocities and associated confidence intervals.

A potential source of error may exist when using predictions calculated from tide height values which are outside of the range of values used for the initial regression analysis. For example, if all casts were acquired during a neap tide period, such as was the case for stations 2N and 2S, velocities predicted by the regression analysis for high or low tide heights of a spring tide period are subject to error. For stations 4SB and 4SA, predictions were calculated using a 9.0-foot tide height; station 4SB (Figure 3.2) was occupied during higher high tide, whereas station 4SA (Figure 3.3) was not occupied during this period. The second- and third-order analysis predicted velocities which probably were not physically possible at station 4SA. Therefore, a basic objective in using polynomial regression models for mean sound velocity predictions and corrections should be the determination of the maximum and minimum velocities expected, and the minimum range of tide where these velocities could occur. The most accurate method for identification of these values would be to measure the sound velocity variables at the same location covering more phases

of the lunar cycle. The danger of predicting outside of the observed range is illustrated by Figure 3.3, whereas Figure 3.2 shows that predicting within the observed range can be done accurately.

Determination of the most efficient polynomial regression analysis to use for prediction of mean sound velocity was accomplished by examination of plots of the data arrays and comparison of the calculation of predicted velocities and confidence intervals provided by each analysis.

(1) *Data Array Plots*. Examination of the data array plots indicated that the first-order (linear) analysis would be sufficient for most of the data arrays, although some of the arrays did suggest a curvilinear trend. Curvature could be detected in the plots of stations 4NA, 4SB (Figure 3.2), 4SA (Figure 3.3), and 4NB (Figure 3.4), with maximum curvature in the plots of stations 4SA and 4SB. This may be an indication that the degree of curvature is proportional to the range of tide since data for stations 4SA and 4SB were acquired during the spring tide period, whereas data acquisition for stations 4NA and 4NB was carried out during a period of average tide range. This hypothesis cannot be verified without further investigation.

(2) *Predicted Velocities*. A computer program was written to predict the mean velocity for five different heights of tide with the maximum and minimum heights being the same as those used in the regression analysis. The other three heights were equally spaced between the maximum and minimum. Rarely was there a significant difference (plus or minus 4 meters per second) between the predictions calculated by the three orders of polynomial regression (Table XIV). Mean velocities predicted using the the third-order regression analysis were in error for stations 2S and 5NB at the 13-meter depth. The cause of this error could not be explained.

(3) *Confidence Intervals*. Confidence intervals (Table XV) were computed for the predicted velocities using t values for 90-percent confidence. In general terms, the confidence intervals were larger for all stations in the 1- and 3-meter depths, with the intervals becoming less with increasing depth. This corresponds with the lower

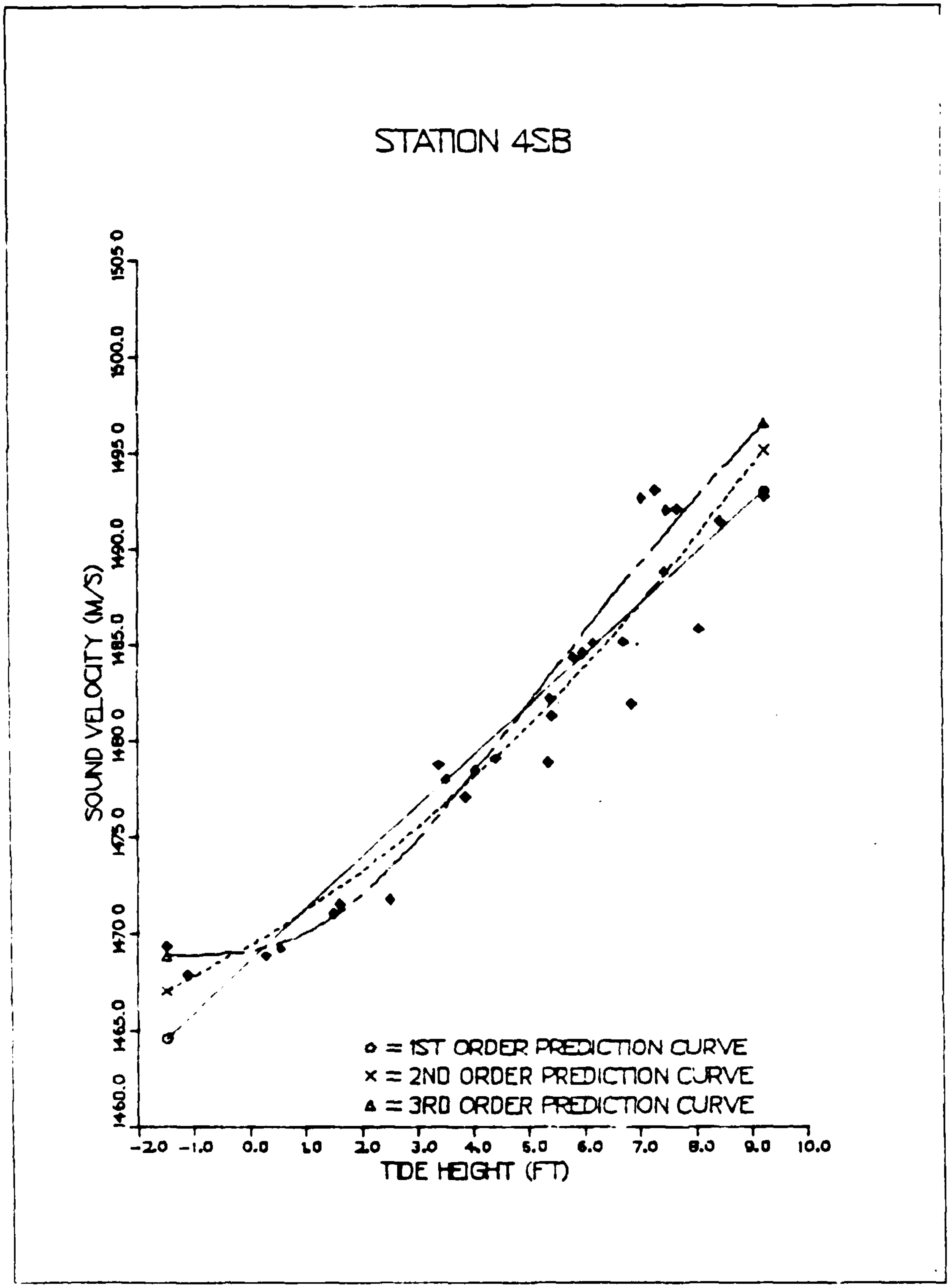

Figure 3.2 4SB--Prediction Curves--Depth = 5 m.

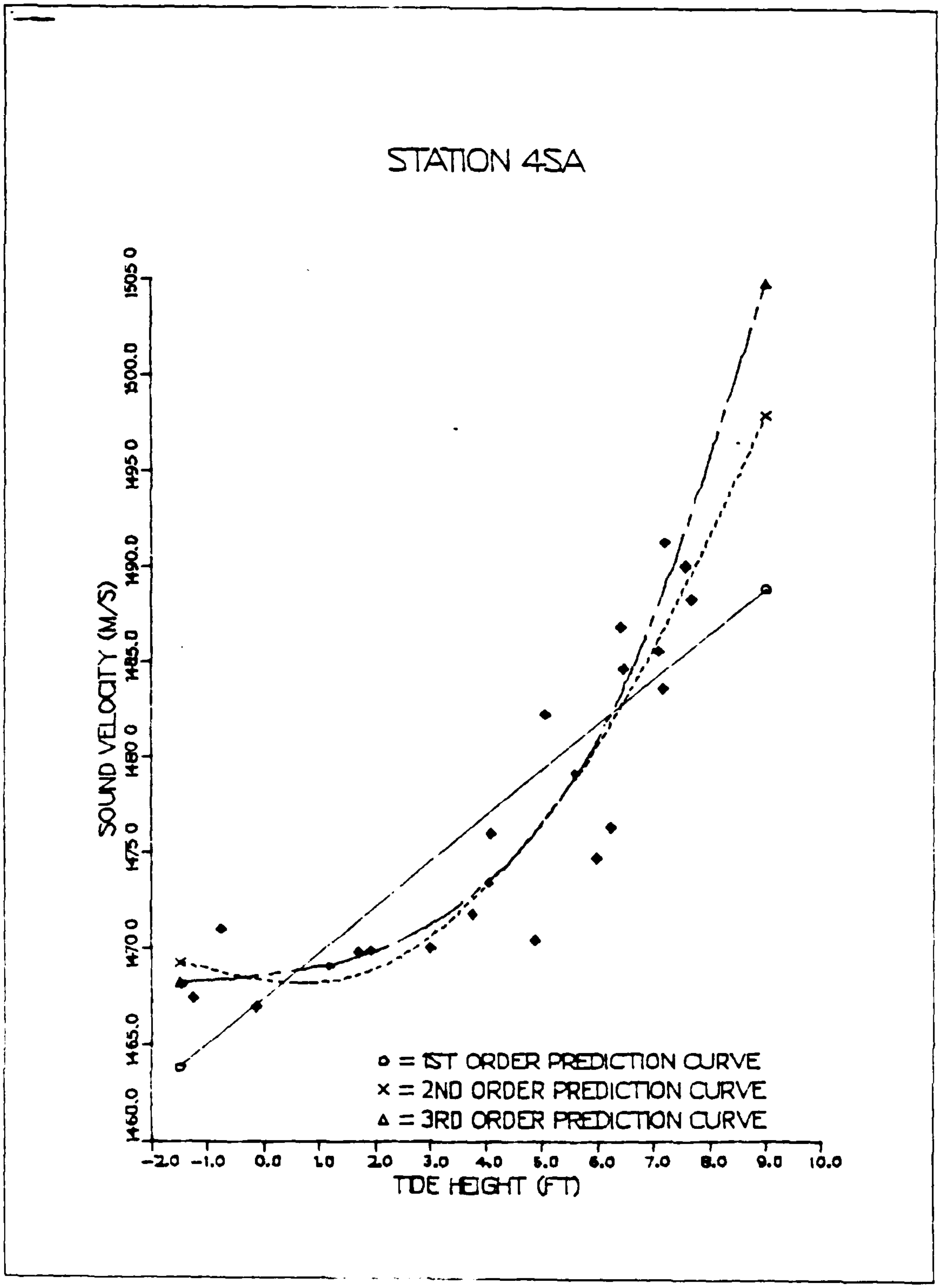

Figure 3.3 4SA--Prediction Curves--Depth = 5 m.

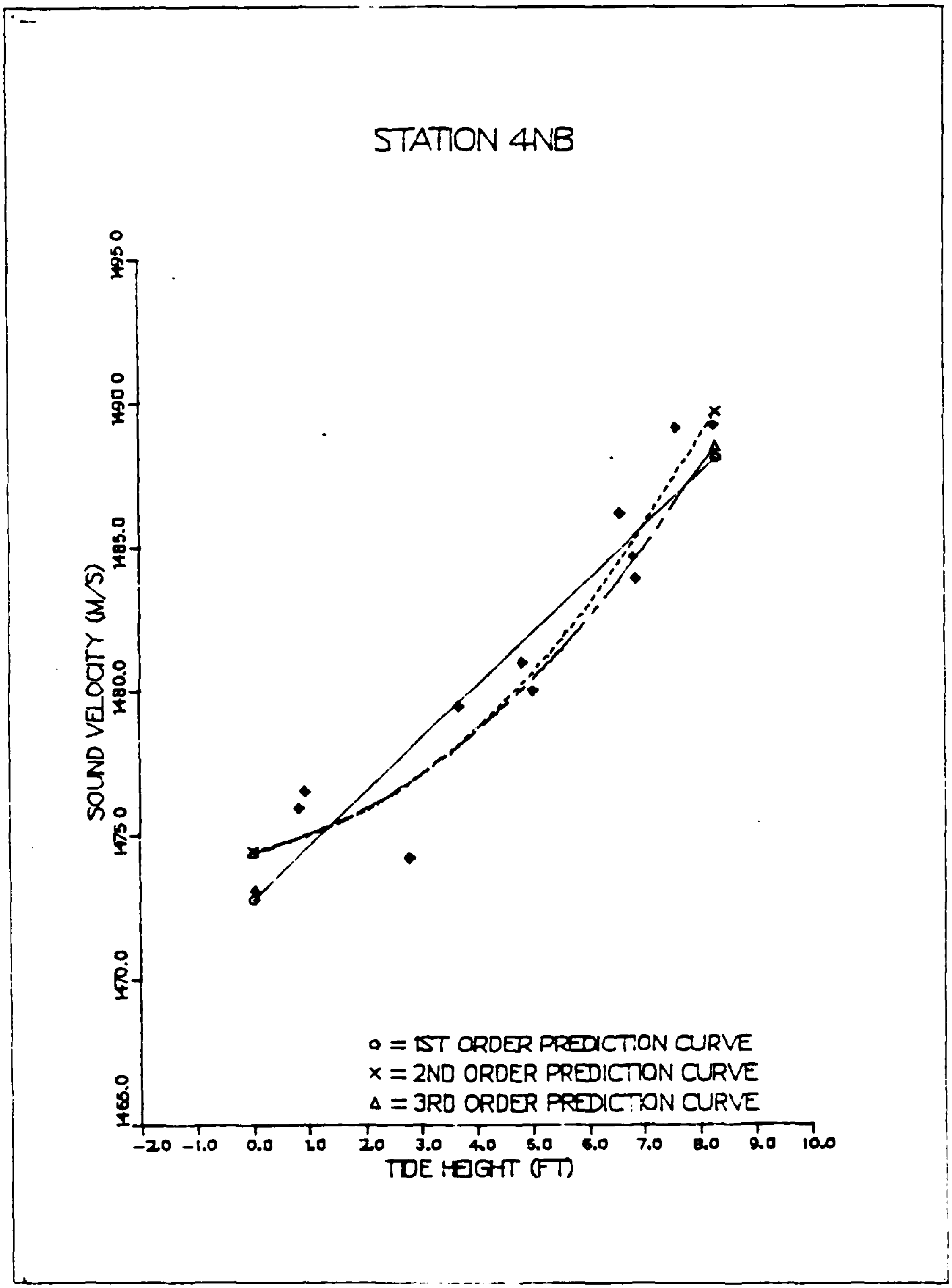

Figure 3.4 4NB--Prediction Curves--Depth = 5 m.

TABLE XIV

Predicted Velocities--Depth = 5 m

STN 2N	TIDE HEIGHT (ft) 1.2	2.6	4.0	5.5	6.9
ORDER					
1	1475.5	1479.0	1482.5	1486.2	1489.7
2	1474.8	1478.9	1482.7	1486.2	1489.2
3	1474.1	1479.3	1482.5	1485.3	1488.7

STN 2S	TIDE HEIGHT (ft) 0.3	1.9	3.6	5.2	6.9
ORDER					
1	1476.8	1480.0	1483.3	1486.5	1489.9
2	1479.5	1479.6	1481.9	1486.1	1492.8
3	1479.3	1479.8	1481.9	1486.0	1493.1

STN 4NB	TIDE HEIGHT (ft) 0.0	2.1	4.1	6.2	8.3
ORDER					
1	1472.8	1476.6	1480.3	1484.2	1488.0
2	1474.4	1475.9	1478.8	1483.5	1489.6
3	1474.4	1476.0	1478.8	1482.9	1488.5

STN 4SB	TIDE HEIGHT (ft) -1.5	1.2	3.8	6.5	9.2
ORDER					
1	1465.0	1471.5	1477.8	1484.3	1490.8
2	1469.2	1471.1	1475.9	1483.9	1494.9
3	1469.5	1470.9	1475.6	1482.9	1491.4

STN 5NB	TIDE HEIGHT (ft) 0.2	2.2	4.2	6.2	8.3
ORDER					
1	1468.9	1472.4	1476.0	1479.6	1483.4
2	1470.5	1472.0	1475.0	1479.3	1485.2
3	1471.1	1471.5	1475.3	1480.6	1485.7

STN 5SA	TIDE HEIGHT (ft) -1.6	1.2	4.0	6.7	9.5
ORDER					
1	1460.2	1463.1	1465.9	1468.6	1471.5
2	1461.6	1462.7	1465.0	1468.3	1473.1
3	1461.9	1462.5	1464.7	1467.2	1468.8

ORDER = Degree of polynomial regression

correlation coefficients found in the shallow depths. Larger confidence intervals were also found for data acquired at stations 2N, 2S, 4SA, and 4SB. These stations had lower correlation coefficients and higher residuals when compared to the other stations. For stations 2N and 2S, this may indicate less stability due to the close proximity of the open ocean. As stated before, data for stations 4SA and 4SB were acquired during spring tide conditions, which tends to indicate less stability for prediction.

In most cases, increasing the degree of the regression analysis did not produce more accurate results in terms of confidence intervals. The standard error of estimate was sometimes lower with a higher order analysis, but the reduction in the degrees of freedom countered the effect of the lower standard error of estimate for computation of confidence intervals.

Confidence interval results indicate that correcting soundings for mean velocity variation based on predictions provided by the regression analysis cannot be considered a complete success. Attaining the goal of predictions to within plus or minus 4 meters per second may not be possible in some cases, but the regression analysis does show a significant reduction in error when compared to only using average velocity and horizontal variation as the correction procedure.

B. NOS BAR CHECK DATA

Analysis of the bar check data revealed too many inconsistencies and required too much speculation for comparison of the CREDDP data results. A major problem of the direct comparison method of the bar check is that examination of the sound velocity variables and any change in their magnitude is not possible. The bar check data did indicate the possibility of either an extremely high sound velocity variation or an instrument error which was not constant with depth. Most likely, the results show an undeterminable combination of sound velocity variation and instrument error. The problem of using the bar check data for any meaningful analysis is illustrated by Table XVI.

TABLE XV

Confidence Intervals--Depth = 5 m

STN		TIDE HEIGHT (FT)			
2N	1.2	2.6	4.0	5.5	6.9
ORDER					
1	4.2	3.9	3.8	3.8	4.0
2	4.1	3.9	3.7	3.7	3.9
3	4.3	4.0	3.9	3.9	4.1
STN		TIDE HEIGHT (FT)			
2S	0.3	1.9	3.6	5.2	6.9
ORDER					
1	4.3	4.1	4.0	4.1	4.3
2	3.8	3.6	3.5	3.6	3.7
3	3.9	3.7	3.6	3.7	3.8
STN		TIDE HEIGHT (FT)			
4NB	0.0	2.1	4.1	6.2	8.3
ORDER					
1	3.1	2.9	2.8	2.8	3.0
2	2.9	2.7	2.6	2.7	2.8
3	3.3	3.1	3.0	3.0	3.2
STN		TIDE HEIGHT (FT)			
4SB	-1.5	1.2	3.8	6.5	9.2
ORDER					
1	5.2	5.0	4.9	4.9	5.1
2	4.9	4.7	4.6	4.6	4.8
3	4.9	4.7	4.6	4.6	4.8
STN		TIDE HEIGHT (FT)			
5NB	0.2	2.2	4.2	6.2	8.3
ORDER					
1	3.3	3.2	3.2	3.2	3.3
2	3.0	3.0	2.9	2.9	3.1
3	2.9	2.8	2.8	2.8	2.9
STN		TIDE HEIGHT (FT)			
5SA	-1.6	1.2	4.0	6.7	9.5
ORDER					
1	3.9	3.8	3.7	3.8	3.9
2	3.6	3.5	3.5	3.5	3.6
3	4.5	4.4	4.4	4.4	4.6

units = ± m/s

TABLE XVI

Bar Check Correction Data for Survey H-8422

OBS	MEAN ft	UPPER LIMIT ft	LOWER LIMIT ft	RANGE ft	DEPTH ft	DEL V m/s
88	-1.0	-0.6	-1.4	0.8	5	231.5
90	-0.8	-0.2	-1.4	1.2	10	177.5
90	-0.7	-0.1	-1.4	1.3	15	124.4
90	-0.7	0.0	-1.3	1.3	20	93.5
90	-0.7	0.1	-1.4	1.5	25	88.3
87	-0.7	0.0	-1.6	1.6	30	78.4
82	-0.6	0.0	-1.3	1.3	35	53.5
73	-0.5	0.0	-1.2	1.2	40	44.4
30	-0.3	0.6	-1.1	1.7	45	55.5

DEL V represents the magnitude of velocity difference necessary to compensate for the range of the corrections if there were no instrument error.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Investigation of sound velocity variation in the Columbia River estuary revealed the following significant findings:

Sound velocity variation in certain areas required the examination of how veloctiy changed with time and location if NOS accuracy standards were to be met. The procedure of computing only one corrector table based on an average velocity, or correction, was not acceptable.

CREDDP data analysis showed a strong relationship between tide height and sound velocity, which stimulated the development of a method to account for the variation of sound velocity with time. Using a regression analysis, the accuracy of velocity correctors was improved significantly, although there were still instances where NOS standards could not be met.

NOS bar check data analysis showed a significant variation in corrections, although the variation did not correlate with tide height as the CREDDP data did. Analysis of the variation found at each 5-foot increment of depth revealed inconsistencies which could not be explained.

B. RECOMMENDATIONS

The following recommendations are made:

Further study of sound velocity variation must be carried out for verification of ideas and methods presented in this thesis. Analysis of data acquired over longer time periods at the same locations will allow a more complete study of the variation associated with different lunar phases and the effect of changes in river flow. NOS CTD data were acquired in the Columbia River estuary during the same time period as CREDDP; these data may allow study of the sound velocity variation over longer time periods.

NOS bar check data analysis showed that the hydrographer should be equipped with an efficient method of measuring sound velocity in addition to determining instrument error. Knowing the value of sound velocity, detection of significant changes and trends is more efficient and accurate. Bar checks should not be used as the primary method of correcting soundings, but should be reserved for determination of instrument error.

Hydrographers conducting surveys in areas where reversing tides could cause a significant variation in sound velocity may benefit by noting the height of tide for each cast or bar check acquired for determining sound velocity corrections. If significant variation is detected, the possibilty of predicting and correcting for temporal variation using the tide height as an independent variable should be investigated. FORTRAN computer programs written for the methods presented in this thesis are listed in Appendices A, B, C, D, E, and F.

In areas where temporal variation of sound velocity is significant, the hydrographer may benefit by using a sound velocimeter to correct soundings. The velocimeter would require only a few minutes to deploy and retrieve. The hydrographer could determine sound velocity periodically throughout the working day without significantly hindering operations.

APPENDIX A

FORTRAN PROGRAM PACKAGE--SOUND VELOCITY COMPUTATIONS

```
C
C
C
C   ***********************************
C   *                                 *
C   *    SOUND VELOCITY COMPUTATIONS  *
C   *                                 *
C   *          JOHN D. WILDER         *
C   *                                 *
C   *            MARCH 1985           *
C   *                                 *
C   ***********************************
C
C
C
C   THIS PROGRAM COMPUTES SOUND VELOCITY USING WILSON'S EQUATIONS AND
C   MEAN OR HARMONIC SOUND VELOCITY USING THE TRAPEZOIDAL METHOD.
C
C
C
      IMPLICIT REAL*4 (A-H,O-Z)
      CHARACTER*51 H(8)
```

```
      CHARACTER*13 H1
      CHARACTER*11 DATE
      CHARACTER*12 H2
      INTEGER TH
      CHARACTER*1 H3
      INTEGER TM
      CHARACTER*6 STN
      DIMENSION D(40),S(40),T(40),SVL(40),P(40),VP(40),VT(40),VS(40),
     *A1(40),A2(40),A3(40),A4(40),P1(40),SVLA(40),HVL(40)
C     DESIGNATE STATION.
      STN='4SB'
C     ENTER NUMBER OF CAST OBSERVATIONS.
      L=31
      M=1
      K=1
C     READ IN HEADER DATA FOR THE CAST.
      DO 10 I=1,L
        SVLT=0.0
        N=0
        DO 5 J=1,4
          READ(4,70) H(J)
70        FORMAT(A51)
5       CONTINUE
        READ(4,80) H1,DATE,H2,TH,H3,TM
80      FORMAT(1X,A13,A11,3X,A12,1X,I2,A1,I2)
```

```
      THO=TH+0.0
      TMI=((TM+0.0)/10.0)/6.0
      TIME=THO+TMI
      WRITE(7,75)
75    FORMAT(//,1X,'STATION',7X,'DATE',8X,'TIME')
      WRITE(7,85) STN,M,DATE,TIME
85    FORMAT(2X,A3,I2,4X,A11,4X,F5.2,/)
      DO 15 J=1,4
        READ(4,90) H(J)
90      FORMAT(A51)
15    CONTINUE
      DO 20 J=1,30
C  READ IN PRESSURE, DEPTH, TEMPERATURE, AND SALINITY.
      READ(4,110) P1(J),D(J),T(J),S(J)
        IF(P1(J).EQ.9999.99) GO TO 30
C  IF PRESSURE IS IN DECIBARS USE THE FOLLOWING EQUATION.
        P(J)=P1(J)*1.019716E-1
C  BEGIN CALCULATION USING WILSON'S EQUATIONS.
        VT(J)=T(J)*(4.5721-T(J)*(.044532-T(J)*(2.6045E-4+T(J)*(7.9851E
     *-6))))
        VP(J)=P(J)*(.160272+P(J)*(1.0268E-5+P(J)*(3.5216E-9-P(J)*(3.36
     *03E-12))))
        VS(J)=(S(J)-35.)*(1.39799+(S(J)-35.)*1.69202E-3)
        A1(J)=T(J)*(-.011244+3.1580E-8*P(J)+T(J)*(7.7711E-7+1.5790E-9*
     *P(J)))
```

```
        A2(J)=P(J)*(7.7016E-5-1.2943E-7*P(J))
      A3(J)=P(J)*T(J)*(-1.8607E-4+T(J)*(7.4812E-6+T(J)*(4.5283E-8)))
        A4(J)=P(J)*P(J)*(T(J)*(-2.5294E-7+T(J)*1.8563E-9)+P(J)*T(J)*(-
     *1.9646E-10))
      SVL(J)=1449.14+VT(J)+VP(J)+VS(J)+(S(J)-35.)*(A1(J)+A2(J))+A3(J)+A4
     *(J)
        N=N+1
110   FORMAT(8X,F7.2,F7.2,F7.2,7X,F7.2)
20    CONTINUE
30    CONTINUE
      WRITE(7,95)
95    FORMAT(13X,'SOUND',5X,'MEAN')
      WRITE(7,105)
105   FORMAT(4X,'DEPTH',2X,'VELOCITY',2X,'VELOCITY')
      J=1
      HVL(1)=SVL(1)
      WRITE(7,115) D(1),SVL(1),HVL(1)
115   FORMAT(2X,F7.2,3X,F7.2,3X,F7.2)
C     BEGIN LOOP FOR COMPUTATION OF MEAN SOUND VELOCITY.
      DO 40 J=1,N
        SUM=0.0
        DO 50 K=2,J
          SUM=SUM+((D(K)-D(K-1))*(SVL(K)+SVL(K-1)))/(2*SVL(K)*SVL(K-1))
50      CONTINUE
        HVL(J)=(D(J)-D(1))/SUM
```

```
        IF(J.EQ.1) GO TO 40
C   PRINT DEPTH, SOUND VELOCITY, AND MEAN SOUND VELOCITY.
        WRITE(7,125) D(J),SVL(J),HVL(J)
125     FORMAT(2X,F7.2,3X,F7.2,3X,F7.2)
40    CONTINUE
      WRITE(7,135)
135   FORMAT(2X,'9999.99',3X,'9999.99',3X,'9999.99')
      J=1
      M=M+1
10    CONTINUE
      STOP
      END
```

```
C
C
C       ***********************************
C       *                                 *
C       *     PREDICTED TIDE HEIGHT       *
C       *                                 *
C       *        JOHN D. WILDER           *
C       *                                 *
C       *          APRIL 1985             *
C       *                                 *
C       ***********************************
C  THIS PROGRAM COMPUTES THE TIDE HEIGHT BASED ON PREDICTED
C  TIDES AT ANY DESIRED TIME.  THE ALGORITHM IS BASED ON THE
C  ANALYTICAL METHOD PRESCRIBED IN THE HYDROGRAPHIC  MANUAL.
C  PREDICTED TIDES AND DESIRED TIMES MUST BE ENTERED VIA FILE-
C  DEF AND RESULTS ARE OUTPUT VIA FILEDEF.
C
C
C
C
      REAL DT(50),DH(50),TLO,TLQ,THQ,THI,DLO,DLQ,DHI,DHQ,A,B,C,
     *T(50),RAN,RANDIF,SLO,HLO,HHI,HLQ,HHQ,HT(50),HV(50),
```

```
     *LOLIM,TLOLIM,HILIM,THILIM,LQTR,HQTR
      INTEGER I,OBS,HO(50),MI(50),L
      I=1
C  THE NUMBER OF DISIRED TIMES MUST BE ENTERED FOR N.
      N=1
 10   CONTINUE
C  PREDICTED TIMES AND HEIGHTS ARE ENTERED.  A FLAG OF "99" MUST
C  FOLLOW THE LAST PREDICTED TIDE.
      READ(4,100) HO(I),MI(I),HT(I)
 100  FORMAT(I2,I2,1X,F8.4)
      IF(HO(I).EQ.99) GO TO 11
      I=I+1
      GO TO 10
 11   OBS=I-1
      DO 12 I=1,OBS
         T(I)=FLOAT(MI(I))/60.+FLOAT(HO(I))
 12   CONTINUE
      L=OBS-1
C  READ IN TIMES FOR WHICH HEIGHT IS DESIRED.
      DO 25 I=1,N
         READ(4,110) DT(I)
         IF(I.EQ.1) GO TO 25
         IF(DT(I).LT.DT(I-1)) DT(I)=DT(I)+24.0
C        DT(I)=DT(I)+24.0
 110     FORMAT(1X,F5.2)
```

```
 25   CONTINUE
C  BEGIN LOOP FOR COMPUTATIONS
      DO 13 I=1,N
         DO 14 J=2,L
C  DETERMINE IF DESIRED TIME IS ON A RISING OR FALLING TIDE.
              IF(DT(I).LE.T(J).AND.DT(I).GE.T(J-1).AND.HT(J).GT.HT(J-1))
     *        GO TO 15
              IF(DT(I).LE.T(J).AND.DT(I).GE.T(J-1).AND.HT(J).LT.HT(J-1))
     *        GO TO 16
              GO TO 14
 14      CONTINUE
C  BEGIN COMPUTATION FOR RISING TIDE.
 15      TLO=T(J-1)
         THI=T(J)
         HLO=HT(J-1)
         HHI=HT(J)
         TIMDIF=THI-TLO
         RAN=HHI-HLO
         HQTR=HHI-(.25*RAN)
         LQTR=HLO+(.25*RAN)
         RANDIF=(.10*RAN)
         HILIM=HQTR+RANDIF
         LOLIM=LQTR-RANDIF
         THILIM=T(J-1)+(.75*TIMDIF)
         TLOLIM=T(J-1)+(.25*TIMDIF)
```

```
C  DETERMINE IF DESIRED TIME IS ON LOWER PARABOLIC, LINEAR OR
C  UPPER PARABOLIC PORTION OF RISE.
         IF(DT(I).GE.T(J-1).AND.DT(I).LE.TLOLIM) GO TO 17
         IF(DT(I).GE.TLOLIM.AND.DT(I).LE.THILIM) GO TO 18
         GO TO 19
C  COMPUTE HEIGHT FOR LOWER PARABOLIC PORTION OF RISE.
 17      A=(LOLIM-HT(J-1))/((T(J-1)**2)-(2*T(J-1)*TLOLIM)+(TLOLIM**2))
         B=(-2*A*T(J-1))
         C=HT(J-1)+(A*(T(J-1)**2))
         DH(I)=(A*(DT(I)**2))+(B*DT(I))+C
         GO TO 13
C  COMPUTE HEIGHT FOR LINEAR PORTION OF RISE.
 18      SLOPE=(HILIM-LOLIM)/(THILIM-TLOLIM)
         DTS=DT(I)-TLOLIM
         DH(I)=LOLIM+(SLOPE*DTS)
         GO TO 13
C  COMPUTE HEIGHT FOR UPPER PARABOLIC PORTION OF RISE.
 19      A=(HILIM-HT(J))/((T(J)**2)-(2*T(J)*THILIM)+(THILIM**2))
         B=(-2*A*T(J))
         C=HT(J)+(A*(T(J)**2))
         DH(I)=(A*(DT(I)**2))+(B*DT(I))+C
         GO TO 13
C  BEGIN COMPUTATION FOR FALLING TIDE.
 16      THI=T(J-1)
         TLO=T(J)
```

```
      HHI=HT(J-1)
      HLO=HT(J)
      TIMDIF=TLO-THI
      RAN=HHI-HLO
      HQTR=HHI-(.25*RAN)
      LQTR=HLO+(.25*RAN)
      RANDIF=(.10*RAN)
      HILIM=HQTR+RANDIF
      LOLIM=LQTR-RANDIF
      THILIM=T(J-1)+(.25*TIMDIF)
      TLOLIM=T(J-1)+(.75*TIMDIF)
C  DETERMINE IF DESIRED TIME IS ON LOWER PARABOLIC, LINEAR OR
C  UPPER PARABOLIC PORTION OF FALL.
      IF(DT(I).LE.T(J).AND.DT(I).GE.TLOLIM) GO TO 20
      IF(DT(I).LE.TLOLIM.AND.DT(I).GE.THILIM) GO TO 21
      IF(DT(I).LE.THILIM.AND.DT(I).GE.T(J-1)) GO TO 22
C  COMPUTE HEIGHT FOR LOWER PARABOLIC PORTION OF FALL.
 20   A=(LOLIM-HT(J))/((T(J)**2)-(2*T(J)*TLOLIM)+(TLOLIM**2))
      B=(-2*A*T(J))
      C=HT(J)+(A*(T(J)**2))
      DH(I)=(A*(DT(I)**2))+(B*DT(I))+C
      GO TO 13
C  COMPUTE HEIGHT FOR LINEAR PORTION OF FALL.
 21   SLOPE=(HILIM-LOLIM)/(THILIM-TLOLIM)
      DTS=DT(I)-THILIM
```

```
           DH(I)=HILIM+(SLOPE*DTS)
           GO TO 13
C  COMPUTE HEIGHT FOR UPPER PARABOLIC PORTION OF FALL.
 22        A=(HILIM-HT(J-1))/((T(J-1)**2)-(2*T(J-1)*THILIM)+(THILIM**2))
           B=(-2*A*T(J-1))
           C=HT(J-1)+(A*(T(J-1)**2))
           DH(I)=(A*(DT(I)**2))+(B*DT(I))+C
           GO TO 13
 13     CONTINUE
C  WRITE VALUES OF HEIGHTS FOR DESIRED TIMES.
        DO 23 I=1,N
C          DT(I)=DT(I)-24.0
           WRITE(7,120) DT(I),DH(I)
 120       FORMAT(1X,F5.2,1X,F5.2)
 23     CONTINUE
C  PLACE FLAG AT END OF DATA
        WRITE(7,125)
 125    FORMAT(1X,'99.99')
        STOP
        END
```

APPENDIX C

FORTRAN PROGRAM PACKAGE--BASIC STATISTICS.

```
C
C
C
C   ************************************
C   *                                  *
C   *        BASIC STATISTICS          *
C   *                                  *
C   *         JOHN D. WILDER           *
C   *                                  *
C   *           APRIL, 1985            *
C   *                                  *
C   ************************************
C
C
C
C   THIS PROGRAM WAS DESIGNED TO COMPUTE THE AVERAGE AND STANDARD
C   DEVIATION OF THE OBSERVED SOUND VELOCITIES AND TIDE HEIGHTS.
C   THE CORRELATION COEFFICIENT FOR TIDE HEIGHT VERSUS SOUND
C   VELOCITY IS ALSO COMPUTED.  A HIGH CORRELATION COEFFICIENT (R > 0.7)
C   MAY INDICATE THAT SOUND VELOCITY CAN BE PREDICTED BASED ON TIDE
C   HEIGHT VIA REGRESSION ANALYSIS.
C
```

```
C
C
      IMPLICIT REAL*4 (A-H,O-Z)
      REAL*4 T(100),V(100),SUMT,SUMV,SUMVT,SUMV2,SUMT2,SDT,SDV,SDTI,
     *SDVI,R
      CHARACTER*3 STN(99)
C   THE FOLLOWING LOOP WAS DEVISED TO ALLOW THE STATISTICAL ANALYSIS
C   TO BE RUN FOR A NUMBER OF DIFFERENT STATIONS CONSECUTIVELY.
      DO 5 J=1,11
C   READ IN STATION IDENTIFICATION.
        READ(4,90) STN(J)
 90     FORMAT(A3)
        SUMT2=0.0
        SUMV2=0.0
        SUMT=0.0
        SUMV=0.0
        SUMVT=0.0
        SDT=0.0
        SDV=0.0
        N=0
C   READ IN TIDE HEIGHTS AND OBSERVED SOUND VELOCITIES.  A FLAG OF
C   999.99 IS TO BE PUT AFTER THE LAST VELOCITY TO SIGNAL END OF LOOP.
        DO 10 I=1,50
          READ(4,100) T(I),V(I)
 100      FORMAT(7X,F5.2,1X,F7.2)
```

```
      IF(V(I).EQ.999.99) GO TO 20
      N=N+1
      SUMT=SUMT+T(I)
      SUMV=SUMV+V(I)
      SUMVT=SUMVT+(V(I)*T(I))
      SUMT2=SUMT2+(T(I)**2)
      SUMV2=SUMV2+(V(I)**2)
10    CONTINUE
20    CONTINUE
C   COMPUTE AVERAGE TIDE HEIGHT AND VELOCITY.
    AVT=SUMT/N
    AVV=SUMV/N
    DO 30 I=1,N
      SDT=SDT+((T(I)-AVT)**2)
      SDV=SDV+((V(I)-AVV)**2)
30  CONTINUE
C   COMPUTE STANDARD DEVIATION OF TIDE HEIGHT AND SOUND VELOCITY.
    SDTI=SQRT(SDT/(N-1))
    SDVI=SQRT(SDV/(N-1))
C   COMPUTE CORRELATION COEFFICIENT.
    R=((N*SUMVT)-(SUMT*SUMV))/SQRT(((N*SUMT2)-(SUMT**2))*((N*SUMV2)-
   *(SUMV**2)))
C   PRINT STATION, AVERAGES, STANDARD DEVIATIONS, AND CORRELATION
C   COEFFICIENT.
    WRITE(7,110) STN(J),AVT,SDTI,AVV,SDVI,R
```

```
110     FORMAT(1X,A3,2X,F5.1,2X,F5.1,2X,F7.1,2X,F5.1,2X,F5.2)
5      CONTINUE
       STOP
       END
```

APPENDIX D

FORTRAN PROGRAM PACKAGE--FIRST-ORDER REGRESSION.

```
C
C
C
C   ************************************
C   *                                  *
C   *       LINEAR REGRESSION          *
C   *                                  *
C   *        JOHN D. WILDER            *
C   *                                  *
C   *           MAY 1985               *
C   *                                  *
C   ************************************
C
C
C
C   THIS PROGRAM WAS DESIGNED TO COMPUTE THE COEFFICENTS A1 AND A2
C   OF THE LINEAR EQUATION Y = A1 + A2*X, WHERE Y IS THE PREDICTED
C   SOUND VELOCITY AND X IS THE TIDE HEIGHT.  IF THERE IS GOOD
C   CORRELATION BETWEEN TIDE HEIGHT AND SOUND VELOCITY, THIS PROGRAM
C   MAY ALLOW HYDROGRAPHERS TO CORRECT FOR THE TEMPORAL VARIATION OF
C   SOUND VELOCITY.
C
```

```
C
C
      INTEGER B,I,M
      CHARACTER*3 STN(99)
      DIMENSION HT(50),V(50),ER(50)
      REAL A1,A2,C,D,E,F,G,SUM1,SUM2
C   THE FOLLOWING LOOP WAS DEVISED TO ALLOW THE REGRESSION ANALYSIS
C   TO BE RUN FOR A NUMBER OF DIFFERENT STATIONS CONSECUTIVELY.
      DO 5 J=1,11
C   READ IN STATION IDENTIFICATION.
         READ(4,90) STN(J)
 90      FORMAT(A3)
         B=0
         C=0.0
         D=0.0
         E=0.0
         G=0.0
         A1=0.0
         A2=0.0
C   READ IN TIDE HEIGHTS AND OBSERVED SOUND VELOCITIES.  A FLAG OF
C   999.99 IS TO BE PUT AFTER THE LAST VELOCITY TO SIGNAL END OF LOOP
           DO 10 I=1,50
              READ(4,100) HT(I),V(I)
 100          FORMAT(7X,F5.2,1X,F7.2)
              IF(V(I).EQ.999.99) GO TO 20
```

```
            B=B+1
            C=C+HT(I)
            D=D+(HT(I)**2)
            E=E+V(I)
            G=G+(HT(I)*V(I))
 10       CONTINUE
 20       CONTINUE
C   COMPUTE COEFFICIENTS A1 AND A2.
          A1=(E-((C*G)/D))*(1/(B-((C**2)/D)))
          A2=(G-(A1*C))/D
C   PRINT STATION ID AND COEFFICIENTS OF PREDICTION EQUATION.
          WRITE(7,125) STN(J),A2,A1
 125      FORMAT(7X,A3,3X,F5.2,3X,F8.2)
          SUM1=0.0
          SUM2=0.0
C   BEGIN LOOP FOR CALCULATION OF RESIDUALS, SUM OF RESIDUALS, AND
C   SUM OF RESIDUALS SQUARED.
          DO 30 I=1,B
            ER(I)=V(I)-(A2*HT(I))-A1
            SUM1=SUM1+ABS(ER(I))
            SUM2=SUM2+(ER(I)**2)
C   PRINT OBSERVATION NUMBER AND RESIDUAL.
            WRITE(7,110) I,ER(I)
 110        FORMAT(16X,I2,11X,F6.2)
 30     CONTINUE
```

```
C   PRINT SUM OF RESIDUALS, SUM OF RESIDUALS SQUARED, AND NUMBER OF OBS.
       WRITE(7,125) SUM1,SUM2,B
 125   FORMAT(/,28X,F7.2,3X,F7.2,3X,I2)
 5    CONTINUE
          STOP
          END
```

APPENDIX E

FORTRAN PROGRAM PACKAGE--SECOND-ORDER REGRESSION.

```
C
C
C
C   ************************************
C   *                                  *
C   *     SECOND ORDER REGRESSION      *
C   *                                  *
C   *         JOHN D. WILDER           *
C   *                                  *
C   *            MAY 1985              *
C   *                                  *
C   ************************************
C
C
C
C   THIS PROGRAM WAS DESIGNED TO COMPUTE THE COEFFICIENTS A1, A2, AND
C   A3 OF THE SECOND ORDER POLYNOMIAL EQUATION Y = A1 + A2*X+ A3*X**2,
C   WHERE Y IS THE PREDICTED SOUND VELOCITY AND X IS THE TIDE HEIGHT.
C   IF THERE IS GOOD CORRELATION BETWEEN TIDE HEIGHT AND SOUND VELOCITY,
C   THIS PROGRAM MAY ALLOW HYDROGRAPHERS TO CORRECT FOR THE TEMPORAL
C   VARIATION OF SOUND VELOCITY.
C
```

```
C
C
      INTEGER B,K
      CHARACTER*3 STN(50)
      DIMENSION HT(50),V(50),ER(50)
      REAL A1,A2,A3,C,D,E,F,G,H,L,J,SUM,SUM2
C   THE FOLLOWING LOOP WAS DEVISED TO ALLOW THE REGRESSION ANALYSIS TO
C   BE RUN FOR A NUMBER OF DIFFERENT STATIONS CONSECUTIVELY.
      DO 5 K=1,9
C   READ IN STATION IDENTIFICATION.
        READ(4,90) STN(K)
 90     FORMAT(A3)
        B=0
        C=0.0
        D=0.0
        E=0.0
        F=0.0
        G=0.0
        H=0.0
        L=0.0
        J=0.0
        A1=0.0
        A2=0.0
        A3=0.0
C   READ IN TIDE HEIGHTS AND OBSERVED SOUND VELOCITIES.  A FLAG OF
```

```
C   999.99 IS TO BE PUT AFTER LAST VELOCITY TO SIGNAL END OF LOOP.
        DO 10 I=1,50
           READ(4,100) HT(I),V(I)
 100       FORMAT(7X,F5.2,1X,F7.2)
           IF(V(I).EQ.999.99) GO TO 15
           HT(I)=HT(I)+2.0
           B=B+1
           C=C+HT(I)
           D=D+(HT(I)**2)
           E=E+V(I)
           F=F+(HT(I)**3)
           G=G+(HT(I)*V(I))
           H=H+(HT(I)**4)
           J=J+(V(I)*(HT(I)**2))
 10     CONTINUE
 15     CONTINUE
        L=D-((F**2)/H)
C  COMPUTE COEFFICIENTS A1, A2, AND A3.
        A1=(E-((C/L)*(G-((F*J)/H)))-((D*J)/H)+((D*F)/(H*L)*(G-((F*J)/H))
       */(B+((C/L)*(((D*F)/H)-C))-((D**2)/H)-(((D*F)/(H*L))*(((D*F)/H)-C
       *)
        A2=(G-((F*J)/H)+(A1*(((D*F)/H)-C)))/L
        A3=(J-(A1*D)-(A2*F))/H
C   PRINT STATION ID AND COEFFICIENTS OF PREDICTION EQUATION.
        WRITE(7,120) STN,A1,A2,A3
```

```
  120    FORMAT(7X,A3,3X,3F7.2)
         SUM=0.0
         SUM2=0.0
C   BEGIN LOOP FOR CALCULATION OF RESIDUALS, SUM OF RESIDUALS, AND
C   SUM OF RESIDUALS SQUARED.
         DO 20 I=1,B
           ER(I)=V(I)-(A3*(HT(I)**2))-(A2*HT(I))-A1
           SUM=SUM+ABS(ER(I))
           SUM2=SUM2+(ER(I)**2)
C   PRINT OBSERVATION NUMBER AND RESIDUAL.
           WRITE(7,110) I,ER(I)
 110       FORMAT(16X,I2,11X,F6.2)
 20      CONTINUE
C   PRINT SUM OF RESIDUALS, SUM OF RESIDUALS SQUARED, AND NUMBER OF OBS.
         WRITE(7,125) SUM,SUM2,B
 125     FORMAT(/,28X,F7.2,F8.2,2X,I2)
 5     CONTINUE
       STOP
       END
```

APPENDIX F

FORTRAN PROGRAM PACKAGE--PREDICTED VELOCITY/CONFIDENCE INTERVAL

```
C
C
C   ************************************
C   *                                  *
C   *    PREDICTED VELOCITIES AND      *
C   *      CONFIDENCE INTERVALS        *
C   *                                  *
C   *         JOHN D. WILDER           *
C   *                                  *
C   *           JUNE 1985              *
C   *                                  *
C   ************************************
C
C   GIVEN THE COEFFICIENTS OF FIRST- AND SECOND-ORDER REGRESSION
C   ANALYSES, A TABLE OF STUDENT-T VALUES, AND HEIGHTS OF TIDE, MEAN
C   TIDE HEIGHT, AND STANDARD DEVIATIONS OF OBSERVED TIDE HEIGHTS AND
C   VELOCITIES
 THIS PROGRAM WILL COMPUTE PREDICTED VELOCITIES FOR
C   EACH DESIRED TIDE HEIGHT AND THE ASSOCIATED CONFIDENCE INTERVALS
C   OF THE PREDICTIONS.
C
C
```

```
      REAL V(99),T(99),S(99),H(99),HM(99),SH(99),SV(99),SH2(99),SV2(99),
     *A(99),B(99),LC(99),UC(99),T1(99),WI(99),S2(99),CI(99),A2(99),B2(99
     *),C2(99),T2(99),V2(99),LC2(99),UC2(99),CI2(99),SUM2(99),SUM(99),
     *DEP
      INTEGER N(99),I,K,J,D,K2,L
      CHARACTER*3 ST(99)
C   READ STUDENT-T TABLE VALUES.
      DO 10 I=1,30
         READ(3,120) T1(I)
 120     FORMAT(F5.3)
 10   CONTINUE
C   READ DEPTH OF CAST OR BAR CHECK OBSERVATIONS.
      READ(4,129) DEP
 129  FORMAT(F4.1)
C   THIS LOOP ALLOWS MORD THAN ONE STATION TO BE ANALYZED CONSECUTIVELY
C   I DESIGNATES STATION
      DO 5 I=1,11
C   READ STATION ID, FIRST-ORDER COEFFICIENTS, SUM OF SQUARES OF
C   RESIDUALS, AND NUMBER OF OBSERVATIONS.
         READ(1,100) ST(I),A(I),B(I),SUM(I),N(I)
 100     FORMAT(A3,3X,F7.2,2X,F5.2,2X,F6.2,2X,I2)
C   READ SECOND-ORDER COEFFICIENTS AND SUM OF SQUARES OF RESIDUALS.
         READ(1,101) A2(I),B2(I),C2(I),SUM2(I)
 101     FORMAT(6X,F7.2,2X,F5.2,2X,F5.2,2X,F6.2)
C   READ AVERAGE TIDE HEIGHT, STANDARD DEVIATION OF TIDE HEIGHT, AND
```

```
C    STANDARD DEVIATION OF OBSERVED VELOCITIES.
          READ(2,110) HM(I),SH(I),SV(I)
 110      FORMAT(14X,F4.2,15X,F4.2,4X,F4.2)
C    READ IN TIDE HEIGHTS FOR WHICH PREDICTIONS ARE TO BE BASED.
          READ(4,130) (H(J),J=1,3)
 130      FORMAT(5X,F4.1,8X,F4.1,8X,F4.1)
C    COMPUTE VARIANCE OF SOUND VELOCITY AND TIDE HEIGHT.
          SV2(I)=SV(I)**2
          SH2(I)=SH(I)**2
C    COMPUTE DEGREES OF FREEDOM FOR FIRST- AND SECOND-ORDER ANALYSES.
          K=N(I)-2
          K2=N(I)-3
C    COMPUTED STANDARD ERROR OF ESTIMATE FOR FIRST- AND SECOND-ORDER
C    ANALYSES.
          S(I)=SQRT(SUM(I)/K)
          S2(I)=SQRT(SUM2(I)/K2)
C    COMPUTE STUDENT-T VALUE FOR FIRST-AND SECOND-ORDER ANALYSES.
          IF(K.GT.30) GO TO 25
          T(I)=T1(K)
 25       T(I)=T1(30)
          IF(K2.GT.30) GO TO 26
          T2(I)=T1(K2)
 26       T2(I)=T1(30)
C    PRINT STATION ID AND TIDE HEIGHTS.
          WRITE(7,211) ST(I),(H(J),J=1,5)
```

```
211     FORMAT(//,1X,'STN',15X,'TIDE HEIGHT (FT)',/,1X,A3,3(9X,F6.1),/)
C   BEGIN LOOP FOR PREDICTED VELOCITIES AND CONFIDENCE INTERVALS.
        DO 30 J=1,5
             V(J)= A(I)+(B(I)*H(J))
             LC(J)=(V(J)-(T(I)*S(I)*(SQRT(1+(1/N(I))+((H(J)-HM(I))**2)/
     *((N(I)-1)*SH2(I))))))
             UC(J)=(V(J)+(T(I)*S(I)*(SQRT(1+(1/N(I))+((H(J)-HM(I))**2)/
     *((N(I)-1)*SH2(I))))))
             V2(J)= A2(I)+(B2(I)*H(J))+((H(J)**2)*C2(I))
             LC2(J)=(V2(J)-(T2(I)*S2(I)*(SQRT(1+(1/N(I))+((H(J)-HM(I))
     ***2)/((N(I)-1)*SH2(I))))))
             UC2(J)=(V2(J)+(T2(I)*S2(I)*(SQRT(1+(1/N(I))+((H(J)-HM(I))
     ***2)/((N(I)-1)*SH2(I))))))
             CI(J)=UC(J)-V(J)
             CI2(J)=UC2(J)-V2(J)
30      CONTINUE
C   PRINT PREDICTED VELOCITIES AND ASSOCIATED CONFIDENCE INTERVALS.
        WRITE(7,210) (V(J),CI(J),J=1,5)
210     FORMAT('ORDER',/,2X,'1',2X,5(F7.2,1X,F5.2)
        WRITE(7,211) (V2(J),CI2(J),J=1,5)
210     FORMAT(/,2X,'2',2X,5(F7.2,1X,F5.2)
5     CONTINUE
      STOP
      END
```

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